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THE FRICTION OF COPPER-NICKEL AND
IRON-SULFUR ALLOYS IN AIR AND VACUUM

by



Nikhil Kumar Sarkar

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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The undersigned certify that they have read, and recommend to the
Faculty of Graduate Studies for acceptance, a thesis entitled

THE FRICTION OF COPPER-NICKEL AND
IRON-SULFUR ALLOYS IN AIR AND VACUUM

submitted by

Nikhil Kumar Sarkar

in partial fulfilment of the requirements for the degree of Master of
Science.

ABSTRACT

The friction of copper-nickel alloys on themselves and on steel and of iron-sulfur alloys on steel is studied in air and in vacuum to determine the frictional characteristics of a typical solid solution alloy and a typical two phase alloy.

The friction of copper-nickel alloys on themselves is reduced only slightly by alloying but substantially by the presence of oxides on the surface. This is due to increasing hardness and decreasing energy of adhesion resulting from alloying and the prevention of metal-to-metal contact resulting from oxidation.

The alloy addition does not affect the frictional behaviour of copper-nickel alloys sliding on steel plates but the friction is much less in vacuum than in air. This result is explained in terms of the embrittlement of the surface by oxides which can form in air but not in vacuum.

Iron sulfide can lower or increase the friction of steels depending on the nature of the sulfide film. A decrease in friction is observed both in air and in vacuum for untreated iron riders sliding on 1015 steel coated with iron sulfide. Here the reduction in friction is attributed to the prevention of metal-to-metal contact by the continuous iron-sulfide film. An increase in friction is observed for iron-sulfur alloy riders sliding on untreated 1015 steel both in vacuum and in air. This behaviour is attributed to insufficient lubrication by iron sulfide and to embrittlement of the surfaces by embedded sulfide particles.

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GENERAL REVIEW

1. HISTORICAL DEVELOPMENT

Man has been familiar with the phenomenon of frictional heating since prehistoric times. His engineering interest in friction was primarily the desire to reduce friction forces in transportation. The scientific study of friction is, however, much more recent. The "father of friction research", Leonardo da Vinci was probably the first who consciously investigated pairs of materials. From that time on, scientists have tried to determine the mechanisms behind this interesting phenomenon. In the present section, a brief review of the development of the concept of friction through the centuries will be discussed.

a) Classical Laws:

Leonardo da Vinci performed the earliest systematic experiments on friction. His unpublished findings were later "rediscovered" and extended by Amontons (1699), Coulomb (1785) and Morin (1833) as the classical laws of friction. With simple apparatus, Amontons developed the "roughness hypothesis" which attributes friction to the interlocking of mechanical asperities on the surface of the contacting materials. This was further elaborated and confirmed by Antoine Parent (1704), Leonhard Euler (1748) and Coulomb (1785). Coulomb distinguished between static and kinetic friction and first proposed the concept of molecular attraction in friction which is an important finding in the light of modern research.

b) Adhesion Theory:

Coulomb's theory infers that the smoother the sliding surface the less should be its frictional resistance. But there is a limit to smoothness beyond which friction increases. Since the more perfect the mating surfaces, the greater is the number of points of contact that lie within the range of molecular forces that cause cohesion.

These facts favour the "theory of adhesion" though the "roughness hypothesis" is still held by some authors (Bikerman, 1941). The "adhesion theory" was first proposed by Hardy (1919) and Tomlinson (1929), who suggested that the interaction between molecules is operative only over small distances, of the order of a few angstroms. Long-range forces are not counted since they are too weak and negligible in comparison with the short-range forces. The force is thus effective at those points where atom-to-atom contact is made and the number of these points is proportional to the area of contact between these surfaces. The concept of the real area of contact is thus brought into the picture first by H. Shaw (1886) and then extended largely by Bowden (1938-39).

According to Bowden, the frictional force is dependent not upon the load but on the real area of contact. The effect of load is due to the increase in area of contact by load. The plastic and elastic deformation of metals increases until the true area of contact is sufficient to support the actual load. A light load may produce a pressure high enough to cause adhesion of the points of contact (welding). The frictional resistance of metals is due primarily to the shearing of welds at the points of contact and secondarily to the ploughing of the harder metal through the softer metal.

c) Electrical Theory

This school attributes friction to the production of an electrical double layer when surfaces are rubbed together. The production of static electricity causes the two surfaces to attract each other and thus retards sliding. The size of the electrical charge depends upon the nature of the sliding surfaces and upon the nature, pressure and humidity of the surrounding gas. The effect of the electrical component on friction, however, appears to be negligible as compared to the other factors controlling friction.

2. QUANTITATIVE LAWS OF FRICTION

As reviewed in the previous section, friction is related to adhesion as well as plastic deformation of materials. On the basis of this explanation the quantitative laws of friction will be established.

Following an approximate plastic analysis, on the assumption that elastic deformation does not take place when a surface irregularity exceeds a few degrees (Halliday, 1957), the real area of contact for a typical junction which is in a state of incipient plastic flow has been found to be $A_r = L/p$, where A_r is the real area of contact, p the penetration hardness, as measured by the Brinell, the Vickers or the Knoop test and L the normal load.

During sliding, the frictional force comes into play in the tangential direction. It is given by $F = s.A_r$ where s is the average shear strength of the junction. It cannot be appreciably larger than the shear strength s_a of the weaker contacting material. Otherwise,

the junction would be sheared within the weaker material, rather than at the original interface. Hence, in the limit $s = s_a$.

Therefore, the friction coefficient can be expressed by

$$f = \frac{F}{L} = \frac{s_a A_r}{p_a A_r} = \frac{s_a}{p_a} \quad \text{----- Eq. (1)}$$

where p_a is the penetration hardness of the weaker contacting material. The friction coefficient is thus the ratio of the shear strength and the penetration hardness of the softer of the two contacting surfaces. Here shear strength and penetration hardness are related by some yield criterion and the friction coefficient is thus independent of speed, normal load, surface geometry and roughness.

This law has been found to be true by various authors such as Whitehead (1950), Rabinowicz (1958), Bowden and Hughes (1939), Gwathmey (1951), Bowden and Young (1951).

Green's analysis of the friction coefficient on the basis of slip line field theory results in

$$f = \frac{1}{1 + \pi/2 - 2\gamma}, \quad 0 < \gamma < \pi/4 \quad \text{----- Eq. (2)}$$

where γ is the maximum flank angle.

The equation is in reasonably good agreement with $f = \frac{s_a}{p_a}$.

But in obtaining the equation $f = \frac{s_a}{p_a}$, the effect of surface energy has

been ignored which like the surface tension in a fluid tends to pull the two surfaces together. This effect is more pronounced when the energy of adhesion W_{ab} between two surfaces is high and the penetration hardness

of the softer material is low. An increase in surface energy thus increases the true area of contact which, according to Rabinowicz, raises the friction coefficient to

$$f = \frac{s_a}{p_a} + c \frac{W_{ab}}{p_a} \quad \text{----- Eq. (3)}$$

where c is a constant. Experiments on clean metals (Rabinowicz, 1966) are consistent with the predictions of Equation (3).

OBJECT OF STUDY

Friction is a major concern in the selection of materials for the sliding components of today's machines. There are a number of applications where severe thermal, mechanical or environmental conditions render the use of conventional mineral oils, greases or synthetic lubricants impossible or impractical. The sliding is then confined to metal-to-metal contact only and the friction coefficient will depend upon the surface and bulk properties of the unlubricated metals as predicted by Equation 3.

Various methods have been suggested to replace fluid by solid lubricants to reduce friction and wear in different environments. Hard metals and alloys can be used in sliding systems to obtain low friction coefficients because of their low $\frac{W_{ab}}{p_a}$ ratios (Rabinowicz, 1966). On the other hand, hexagonal metals and alloys characterised by anisotropy and preferred orientation reduce the friction coefficient to a considerable extent (Buckley, 1968).

The compatibility between different metals or alloys is related to the energy of adhesion. The energy of adhesion can be expressed fairly well in terms of the surface tension of the softer material i.e. $W_{ab} = 2\gamma_a$ for highly compatible and $W_{ab} = \frac{1}{2}\gamma_a$ for highly incompatible metals (Rabinowicz, 1966). On the basis of this, a careful selection of a metal pair can result in low friction coefficients. Experimental work by Coffin (1956) indicates that the absence of solid solubility between two metals forming a friction couple is equivalent to a low energy of adhesion.

The energy of adhesion is also lowered by alloying. Alloying, however, is more important since it can reduce friction by the combined effect of

a slight reduction in surface tension γ_a , and an appreciable increase in the hardness of the material. For bronze, the addition of 10% tin to copper will decrease the surface tension by only 10% but double the hardness of copper (Rabinowicz, 1967).

The use of a solid lubricant is another means of reducing friction in sliding and rolling contacts. In order to be effective, the lubricant has to adhere well to the substrate to prevent metal-to-metal contact, it has to have a lower shear strength than the substrate to ensure that shear occurs only in the solid lubricant, and it has to be thin enough to be fully supported by the substrate.

When these conditions are met the friction coefficient, according to Bowden, Tabor (1954), and Rabinowicz (1966), can be expressed by

$$f = af_m + (1-a) f_1 \text{ ----- Eq. (4)}$$

where a is the fraction of the true area of contact over which metallic junctions form, f_m is the friction coefficient of the unlubricated metal pair and f_1 is the friction coefficient of the metal pair lubricated by an unbroken and fully supported film of solid lubricant.

The friction coefficients are given by $f_m = \frac{s_a}{p_a}$ and $f_1 = \frac{s_1}{p_a}$ where s_1 is the shear strength of the lubricant film.

Solid lubricants are frequently resorted to particularly under severe environmental conditions. There are two methods available for obtaining self-lubricating materials. In the first method, a thin coating of lubricant is deposited on the surface. In the second method, the lubricant is incorporated in the structure either by alloying or powder metallurgical techniques.

In the present investigation, the method of alloying is used to study the friction characteristics of copper-nickel and iron-sulfur alloys. The copper-nickel system is chosen as a typical representative of a solid solution alloy. Very little work has been done on the friction of solid solution alloys, which should be lower than that of their constituent metals as already explained. Their frictional behaviour on steel is also studied to determine the effect of compatibility of a dissimilar metal pair.

Iron-sulfur alloys, on the other hand, represent a binary alloy consisting of a ductile matrix and a brittle phase. It has been reported by Buckley and Johnson (1963, 1964) that reduction in friction is achieved with sulfur-treated steels while others (Bowden and Tabor, 1954) claim that brittle phases are ineffective when they are much harder than their matrix. The aim of the present study is to investigate this question in more detail.

All studies are conducted in air of varying relative humidity (RH), water and vacuum to assess further the influence of different environments on the frictional behaviour of the aforementioned alloys.

EXPERIMENTAL

1. SPECIMEN PREPARATION

Riders of copper-nickel alloys of different composition were obtained by vacuum induction melting and subsequent solidification in 1.2 cm inside diameter and 5.0 cm high quartz crucibles. Plates of 10.0 cm diameter and 1.0 cm thickness of the same composition as those of the riders were also prepared by induction melting and casting in a steel mould in air. Both riders and plates were annealed for 24 hours at 2000°F under protective atmosphere except those consisting of pure copper which were annealed for 6 hours at 1800°F.

Riders of iron-sulfur alloys were prepared in the same way as the copper-nickel riders but they were not annealed. An AISI 1015 steel plate was coated with a continuous FeS film by immersion in boiling sulfur for 3 hours. After this treatment the remaining sulfur on the metal surface was dissolved with carbon disulfide. The presence of FeS both in the structure of the riders and on the surface of the AISI 1015 plate was confirmed by x-ray diffraction. The riders were machined into cylinders of 0.8 cm diameter and of 1.2 cm height with a hemispherical end of 0.6 cm radius for the friction surface.

Appendix-I lists the form, purity and supplier of the alloying elements copper, nickel, iron and sulfur.

The steel plates used in the experiments had a diameter of 15.0 cm and a thickness of 0.6 cm. Their designations and conditions are as follows:

AISI 1015 Steel, hot rolled, hardness Rockwell B 65

AISI 304 stainless steel, annealed, hardness Rockwell B 82

AISI 4340 steel, hardened, hardness Rockwell C 48

AISI 01 tool steel, hardened, hardness Rockwell C 65

AISI 01 tool steel, hardened, hardness Rockwell C 38

2. APPARATUS

The friction apparatus used in this investigation was of the pin and disc type. Its major components are shown in Figures 1 and 2. The main element of the system was an instrumented cantilever arm made from AISI-W2 tool steel heat treated to a hardness of Rockwell C 55. The dimensions of the arm were 25.0 x 0.4 x 0.4 cm. The specimen was attached to the arm by a specimen holder which permitted placing it anywhere over the disc.

Four Budd foil strain gauges were attached to the sides of the arm. They formed the two active arms of the Wheatstone bridge. The dummy gauges were attached to the post which served also as fixture for the cantilever arm. The bridge current was supplied by a lead battery and was held constant at 35 mA. The signals from the bridge corresponded to the normal and friction force and were registered on two synchronized EUW-20A Heath Servo Recorders.

The whole friction system was enclosed in a vacuum tight chamber for conducting the environment controlled experiments. The environments selected were air of varying RH, vacuum of 10^{-3} mm Hg and water. The relative humidity was determined with an indicating hygrometer placed into the humidity controlled chamber. The system was evacuated with a two

stage mechanical vacuum pump with a cold trap at -79°C between pump and vacuum system to minimize the backstreaming of hydrocarbons into the vacuum chamber.

3. PROCEDURE

Before each test the discs and the riders were ground with 240 grit size emery paper and then thoroughly washed with acetone to remove any grease or contaminant film.

In all tests the rider was pressed against the plate with a normal load of approximately 400 gms. Readings of the normal load and the friction force were taken after a running-in period of 20 minutes when both had reached their steady-state values.

RESULTS

The friction tests were conducted in air of varying RH, in vacuum of 10^{-3} mm Hg, and in water with the following three types of friction couples:

Group 1, copper-nickel alloy riders and a 52100 steel rider on copper-nickel alloy plates; Group 2, copper-nickel alloy riders on various steel plates; Group 3, iron-sulfur alloy riders on various steel plates and a pure iron rider on a plate of 1015 steel coated with an iron-sulfide film.

Group 1

The influence of the composition on the hardness and the friction coefficient of copper-nickel alloys sliding on themselves is shown in Tables 1 to 6 and Figures 3 and 4. The hardness increases with alloy content and reaches its highest value at 60 percent nickel. The friction coefficient decreases with alloy content and also reaches its lowest value at around 60 percent nickel.

The effect of speed on the friction coefficient of copper-nickel alloys is shown in Tables 3, 7 and 8 and Figure 5. It indicates an increase in the friction coefficient with speed.

The friction coefficients of the 52100 steel rider on copper-nickel alloys show the same dependence on the composition as before and are given in Table 9 and Figure 6. Figure 4 and 11(i) show that the friction coefficients of copper-nickel alloys on themselves are higher in vacuum than in air of 5% RH. They are further decreased by increasing the moisture content of the air. The lowest values are observed in water.

Group 2

Tables 10 to 29 and Figures 7 to 10 show that friction coefficients are independent of the alloy content of copper-nickel alloys sliding on different steel plates in various environments. These figures also indicate no great difference in the friction coefficients observed with the various plate materials. The highest coefficients are found with 304 stainless steel. Not only the alloy content but also the hardness of the steel fails to affect friction appreciably. This is particularly evident for two 01 steel plates with a hardness of Rockwell C 38 and 65 for which essentially the same friction coefficients are obtained.

But the environment has a noticeable effect on the friction coefficients as shown in Figures 11 (ii), 11 (iii), 11 (iv), and 11 (v). In air of high RH they are slightly higher than in air of low RH. In a vacuum of 10^{-3} mm Hg they are, however, surprisingly low and quite close to those obtained with water as a lubricant.

In order to further investigate this behaviour, the surfaces and the debris of friction couples consisting of copper riders on 1015 steel plate and 01 steel plate are studied after friction tests in air and in vacuum under the microscope. Here it is found that the appearance of the wear tracks on the plates and the riders is quite different in vacuum than in air.

Figure 17 shows that in vacuum fairly smooth wear tracks are obtained on the 1015 steel plate and that they are covered by a smeared copper film in certain places. The surface of the hard 01 steel plate is even smoother than that shown in Figure 17. Figure 18 shows that the copper riders are also well polished in vacuum. Furthermore, they are covered

by a thin transferred iron film when in contact with the soft 1015 steel plate and almost free from a transferred film when in contact with the 01 steel plate. Loose wear particles are generally not produced in vacuum. In some tests, however, some severely distorted wear particles form in case of the 1015 steel plate. Figure 19 shows these quite coarse copper and iron particles which have a bright metallic appearance and are free from oxide contamination.

Figure 20 shows the rough surface of the wide wear track on the 1015 steel plate for the tests in air. The harder 01 steel plates have also a somewhat rougher surface in air than in vacuum. Figure 21 shows the rough surface of the copper rider on the 1015 steel plate in air. This rider is covered with many adhering fragments of predominantly iron, whereas the copper rider in contact with the harder 01 steel plate is mainly covered with re-deposited copper particles. Figure 22 shows the much finer wear particles obtained for copper on 1015 steel in air. The amount of debris obtained for this combination is much larger than for the copper 01 steel couple which is more copper rich. Table 37 lists the d-spacings obtained from an x-ray diffraction pattern of these particles, and indicates that the particles consist of Fe, Cu, Fe_3O_4 and possibly $6 \text{ CuO} \cdot \text{Cu}_2\text{O}$.

Group 3

Tables 30 to 33 and Figures 12 and 13 indicate a pronounced increase in hardness and a slight increase in friction of the iron-sulfur alloys with increasing sulfur concentration. The nature of the steel constituting the plate appears to have very little effect on the friction coefficient,

though the friction coefficient obtained with 304 stainless steel is again higher than those determined with the other plates as shown in Figures 13 and 15.

The environment here is also the most important variable. Tables 34 to 36 and Figures 14 and 16 show that friction coefficients decrease with increasing RH and in water they are lower than in other environments. For this group friction is highest in vacuum.

Figure 23 shows the microstructure of an iron rider containing 6.98 percent sulfur. It consists of iron dendrites surrounded by a brittle iron-sulfide network. Figure 24 indicates that the network has been broken up in the friction test and that some of the fragments have become embedded in the matrix.

The friction coefficient of a pure iron rider on a 1015 steel plate covered with a continuous iron sulfide film is only 0.5 both in air and in vacuum.

DISCUSSION

The friction characteristics of the following three groups of material combination will be analysed in the present section:

Group 1

Copper-nickel alloys sliding on themselves and a 52100 steel on copper-nickel alloys, representing a friction couple involving an alloy with complete solid solubility.

Group 2

Copper-nickel alloys on various steels, representing a friction couple where the rider, constituting the smaller surface, is an alloy with complete solid solubility.

Group 3

Iron-sulfur alloys on various steels, representing a friction couple where the rider, constituting the smaller surface, consists of a two phase alloy containing a brittle phase in a ductile matrix.

The effect of environment, i.e. air with varying RH, a vacuum of 10^{-3} mm Hg, and water, as well as the effect of sliding speed on friction will be discussed separately for each of the above groups wherever applicable.

Group 1

The decrease in friction coefficient achieved by alloying copper with nickel, as shown in Figure 4, can be explained in terms of Equation 3. It predicts a decrease in friction with increasing hardness and decreasing energy of adhesion. Since alloying has this very effect on these two parameters, the observed decrease in friction is not surprising.

The even more pronounced effect of the gas atmosphere can be explained in terms of the lubrication offered by the copper-nickel oxides. For the instance of copper oxide, Whitehead (1950) has shown that this oxide is effective as a lubricant as long as the applied load does not exceed a critical value above which the oxide film on the surface breaks up and metal-to-metal contact occurs.

In the present case it is believed that the environment controls the thickness of the oxide layer that can form on the wear track between successive passes. It is further believed that the friction coefficients should decrease with increasing oxide film thickness because of the better protection they offer against metal-to-metal contact. This view is consistent with the ideas expressed by Rabinowicz (1967) in a systematic study of the conditions under which oxides are effective as lubricants.

The drastic increase in friction coefficient observed with increasing speed supports the arguments regarding the beneficial role of oxides since the rate of film reformation will be less at higher speeds than at lower speeds. The coarse wear debris obtained at high sliding speeds can, therefore, be explained in terms of more penetration and the fine debris at low sliding speeds in terms of less penetration of the oxide film.

All this evidence indicates that the surface oxides act as solid lubricants in the manner predicted by Equation 4 and that the factors which cause the film to break up or to be penetrated will result in an increase in the friction coefficient.

The view has often been expressed (de Villemeur, 1956) that for a dissimilar sliding couple the friction coefficient is more influenced by

the nature of the larger surface, which corresponds to the surface of the plate, than by the smaller surface of the rider.

In order to determine whether this effect applies here, a 52100 steel rider was substituted for the copper-nickel alloy riders. The results confirm the above stated view since they show again lower friction at intermediate copper-nickel concentrations than for the pure metals.

The observed level of the friction coefficients is, however, higher than for the copper-nickel alloys on themselves, presumably because of the higher degree of penetration of the oxide film by the hard 52100 steel rider.

Very similar results were obtained by Alison et al (1964-65) who studied the friction of copper-nickel alloys in contact with smoothly cut steel files. They found somewhat higher friction coefficients and less variation of them with composition. The results can be explained in terms of the greater severity of the frictional conditions in case of their friction couple.

It can be concluded for this group that the friction coefficients of solid solution alloys can be lower than those of the constituent pure metals. This effect is retained even if the smaller surface of the rider is of a different metal than the solid solution alloy constituting the larger surface of the plate.

Group 2

Here the friction coefficients depend again essentially on the plate material and not on the composition of the copper-nickel alloys. This explains the absence of any consistent trend in the friction coefficients as a function of the rider composition.

The most interesting results are obtained when the effect of environment is studied. Here the friction coefficients are higher in an oxidizing atmosphere than in a neutral atmosphere, as indicated by the substantially lower friction coefficients in vacuum than in air and the somewhat lower friction coefficients in air of low RH than in air of high RH. These results indicate for the copper-nickel alloy on steel friction couples that surface oxides are undesirable since they increase friction and wear.

Though it has been shown by many authors (Peterson et al, 1960 and Rabinowicz, 1967) that oxide films at the interface of rubbing metals can reduce friction, the opposite behaviour observed in the present investigation has been reported by a few other authors for certain metal combinations. Coffin (1956) found that some metal couples with no mutual solid solubility exhibit less friction in helium than in dry air, and suggested that this behaviour is due to some interaction between the metals and their oxides. The same behaviour has been reported by Begelinger and de Gee (1967) in their study of the frictional characteristics of silver against iron in different environments. They found that the friction coefficient increased when the atmosphere was changed from argon to argon +5% oxygen and suggested that this behaviour might be due to the formation of a thin iron oxide film which "glues" the surfaces together at the points of contact.

In order to determine the mechanism responsible for the observed behaviour, the microstructure of the surface of the 1015 steel plate, the surface of the copper rider and the wear debris were studied as mentioned earlier.

In case of the experiments in air, the surfaces are deeply cratered in certain areas and covered with tightly adhering fragments in others as

shown in Figures 20 and 21. The fine wear particles shown in Figure 22 are identified by x-ray diffraction as Cu, Fe, $6\text{CuO} \cdot \text{Cu}_2\text{O}$ and possibly Fe_3O_4 as can be seen from Table 37.

In vacuum, however, the surfaces are either polished or covered by a thin film of transferred material rather than coarse adhering particles. Also there is no evidence of loose wear particles in most cases. When wear debris is obtained, it has a bright metallic luster rather than the dark appearance observed in air. Furthermore no evidence of oxides can be found when the debris is studied under the microscope, as shown in Figure 19.

On the basis of the above presented observations, it is believed with Coffin and de Gee et al that oxides are indeed responsible for the high friction in air. It is felt, however, that the oxides do not "glue" the surfaces together but that their role is the following:

They form during friction experiments in air on the surface asperities and become folded under in the course of the test. This lowers the ductility of the asperities and they become so brittle that the friction forces tear them out. The particles then either adhere to the other surface or become loose.

It would of course be desirable to investigate the embrittlement of the rubbing surfaces by oxides in more detail than in the present investigation. There is, however, no doubt in the mind of the author that the embrittlement of the surface by oxides has an effect on friction, since it is commonly observed (Wills, 1967, Mantel, 1967 and Erickson, 1967) that the fatigue life and the ductility of steels are lowered by increasing oxide inclusion content.

The low friction coefficients in vacuum can be explained in terms of the absence of the embrittling oxides in the surface of the steel plate and the copper-nickel alloy rider, as well as the lower forces of adhesion between copper and iron as compared to those between the pure metals themselves. Because of these circumstances polishing of the surface occurs, as indicated by Figure 18, and the surface asperities will rather be smoothened out than fractured in fatigue. This explains the absence of finely divided wear particles and the absence of much metal transfer in vacuum.

It can be concluded for this group that the friction of incompatible metal pairs can be higher in air than in a non-oxidizing environment. This effect is attributed to the embrittlement of the surface by the oxides which form on it and then become embedded in it during the friction test.

Group 3

The experiments conducted on the friction couples of this group show that iron sulfide has either no effect on friction or increases it slightly both in air and in vacuum. Furthermore the friction is appreciably higher in vacuum than in air. This indicates that iron sulfide fails to lubricate the friction couple when no oxides are present on the surface. These results are surprising in the light of the work of Johnson and Buckley (1963, 1964) who found the opposite behaviour.

They observed for a number of steels and electrolytic iron sliding on themselves in high vacuum a pronounced reduction in friction when these were alloyed with sulfur. Johnson and Buckley showed too that the

friction coefficients were practically the same no matter whether both rider and plate contained sulfur or only one of them.

In order to find the explanation for the observed discrepancies, the plates and the riders of the present work were investigated metallographically. It was found that some of the iron sulfide in the rider had broken out and a part of the fragments had become embedded in the matrix of the rider as indicated in Figure 24.

Under these conditions, no lubrication can be expected because of Bowden's and Tabor's (1954) findings that brittle compounds are ineffective as lubricants when they become buried in the softer matrix. The larger friction coefficients at high sulfur concentrations are therefore attributed to the increased embrittlement and ploughing of the surface by the protruding iron sulfide particles.

How can these arguments be reconciled with Buckley's and Johnson's results? In case of their steel couples, the surfaces are probably hard enough to resist the embedding of sulfide and to offer good support to it, so that it can become effective as solid lubricant.

In case of their sulfur-modified electrolytic iron, the low friction coefficient may be due to the fact that both the rider and the plate contain sulfur, which according to de Villemeur (1953) is more effective than when only the rider is treated.

In order to find further experimental support for these arguments a 1015 steel plate was coated with a continuous iron sulfide film and run against an untreated iron rider. It was hoped that the friction coefficient would be low since the larger surface was coated and the film was continuous. The results indicate that this is indeed the case since the friction coefficient is only 0.5 both in air and vacuum.

It can be concluded for this group that an alloy consisting of a soft matrix and a hard second phase is not necessarily self-lubricating because the surface may be too soft to support the brittle phase. But a reduction in friction can be realised when a continuous film is formed.

SUMMARY AND CONCLUSIONS

The following three groups of material combination were investigated in air of varying RH and in vacuum:

Group 1, copper-nickel alloys on themselves and a 52100 steel on copper-nickel alloys.

Group 2, copper-nickel alloys on steels.

Group 3, iron-sulfur alloys on steels and iron on steel coated with iron sulfide.

Group 1

The friction characteristics are controlled essentially by the plate material and the reduction in friction obtained by alloying copper with nickel is fairly small. The formation of a sufficiently thick oxide on the surface, however, appears to be more important for obtaining low friction coefficients than the exact alloy composition.

Group 2

Friction is not affected by the composition of the copper-nickel alloys but it is much lower in vacuum than in air. This increase in friction is attributed to the embrittlement of the sliding surfaces by the oxides which become embedded in the surface during the test in air. The higher compatibility of nickel with iron than copper with iron is not found to affect the observed frictional behaviour.

Group 3

Both in air and in vacuum, iron sulfide decreases friction when it forms a continuous film on steel plate sliding against an untreated iron rider and it increases friction when it is present in the structure of a rider

sliding on untreated steel plates. For the latter case, the increase in friction is attributed to the embrittlement of the surface by iron sulfide that becomes buried in it in the course of the friction experiment. This effect is retained in vacuum where the friction coefficients are even higher because of the absence of protective oxides on the surface.

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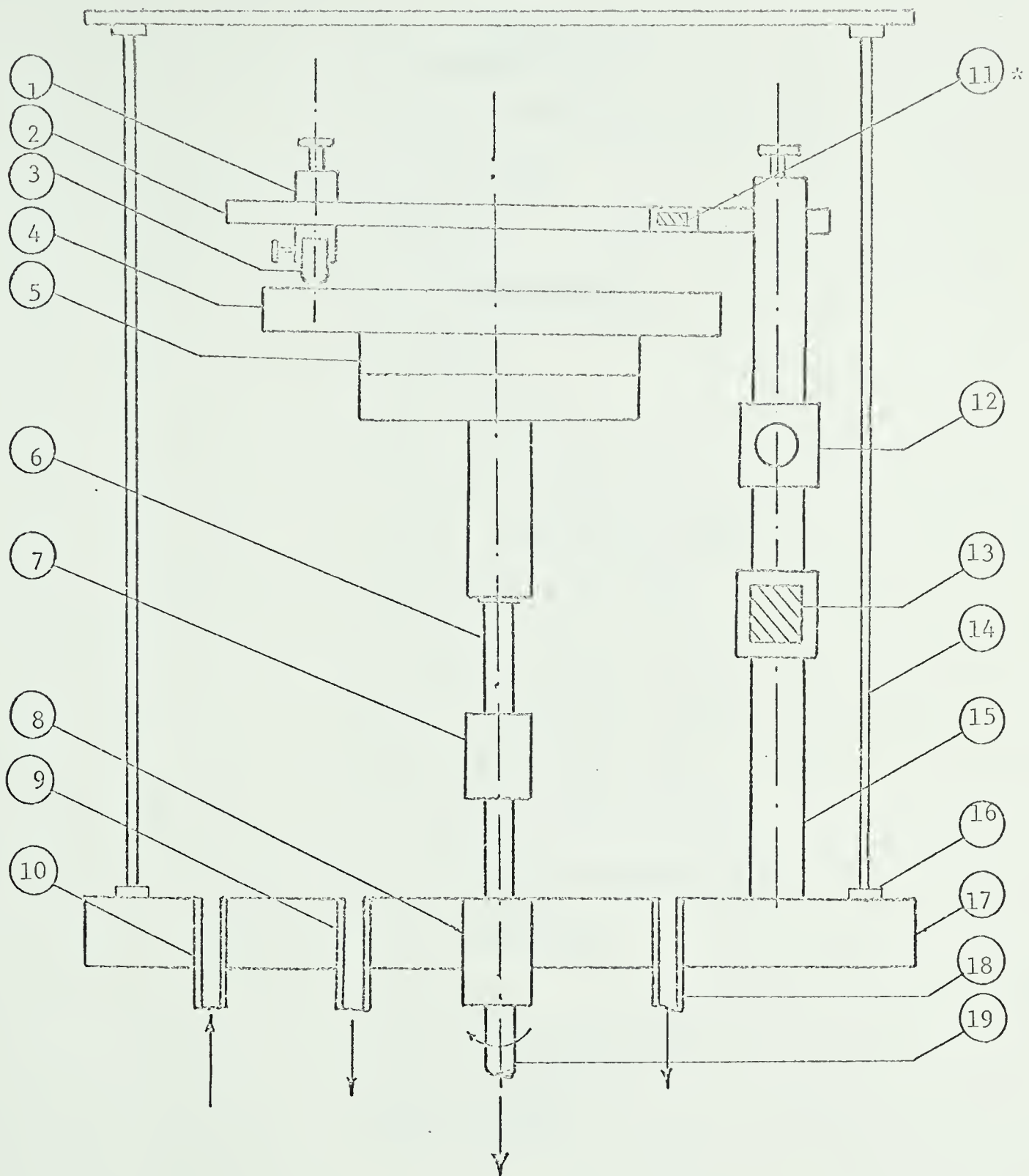
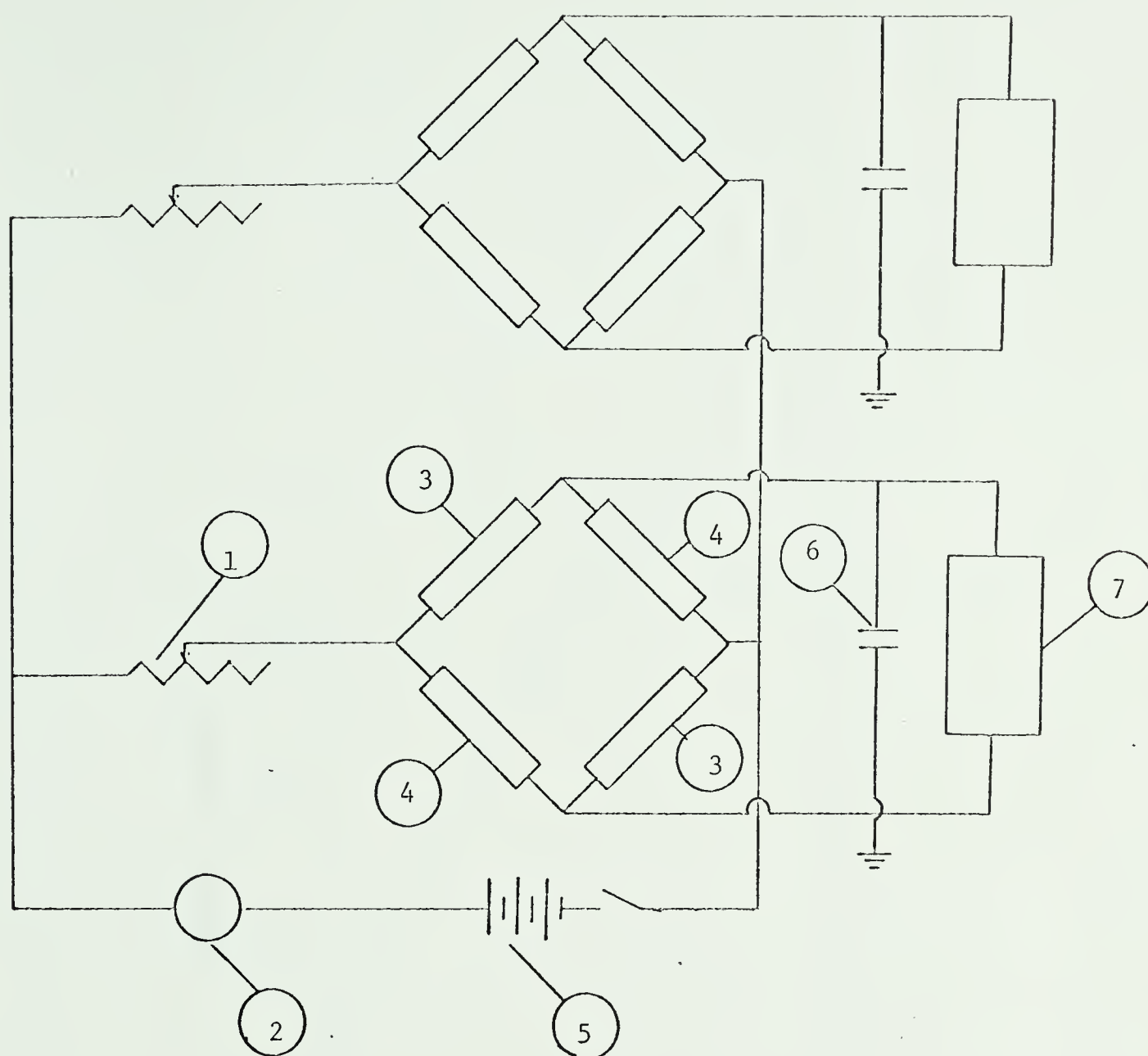


FIG. 1 - SCHEMATIC DIAGRAM OF THE FRICTION APPARATUS

* LEGEND ON PAGE 30

LEGEND OF FIG. 1

- (1) SPECIMEN HOLDER
- (2) INSTRUMENTED CANTILEVER ARM
- (3) SPECIMEN
- (4) PLATE
- (5) TEFLON BEARING
- (6) SHAFT
- (7) COUPLING
- (8) FEED-THROUGH
- (9) TO THERMOCOUPLE GAUGE
- (10) WATER VAPOR INLET
- (11) ACTIVE STRAIN GAUGE
- (12) LOAD ADJUSTING SCREW
- (13) DUMMY STRAIN GAUGE
- (14) VACUUM TIGHT CHAMBER
- (15) POST FOR CANTILEVER ARM
- (16) VACUUM SEAL
- (17) BASE
- (18) TO MECHANICAL PUMP
- (19) TO MOTOR



- (1) VARIABLE RESISTOR
- (2) D.C. AMMETER
- (3) DUMMY STRAIN GAUGE
- (4) ACTIVE STRAIN GAUGE
- (5) BATTERY
- (6) CAPACITOR
- (7) RECORDER

FIG. 2 - CIRCUIT DIAGRAM OF THE FOUR-ARM STRAIN-GAUGE BRIDGE

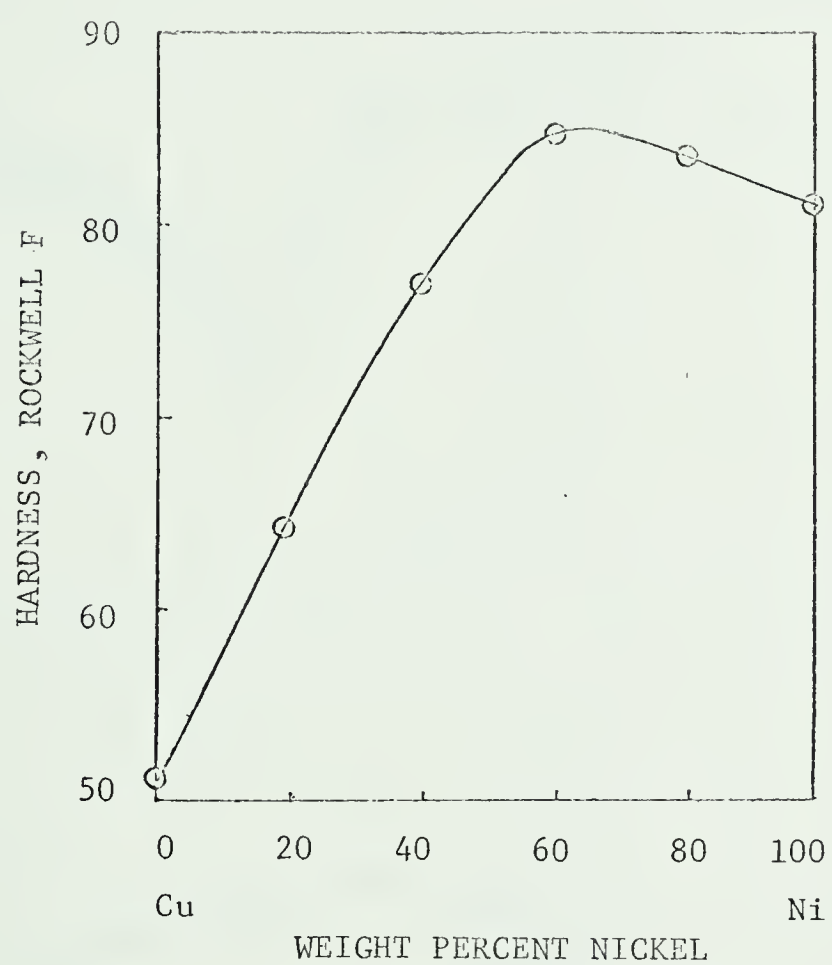


FIG. 3 - VARIATION OF HARDNESS WITH COMPOSITION OF COPPER-NICKEL ALLOYS

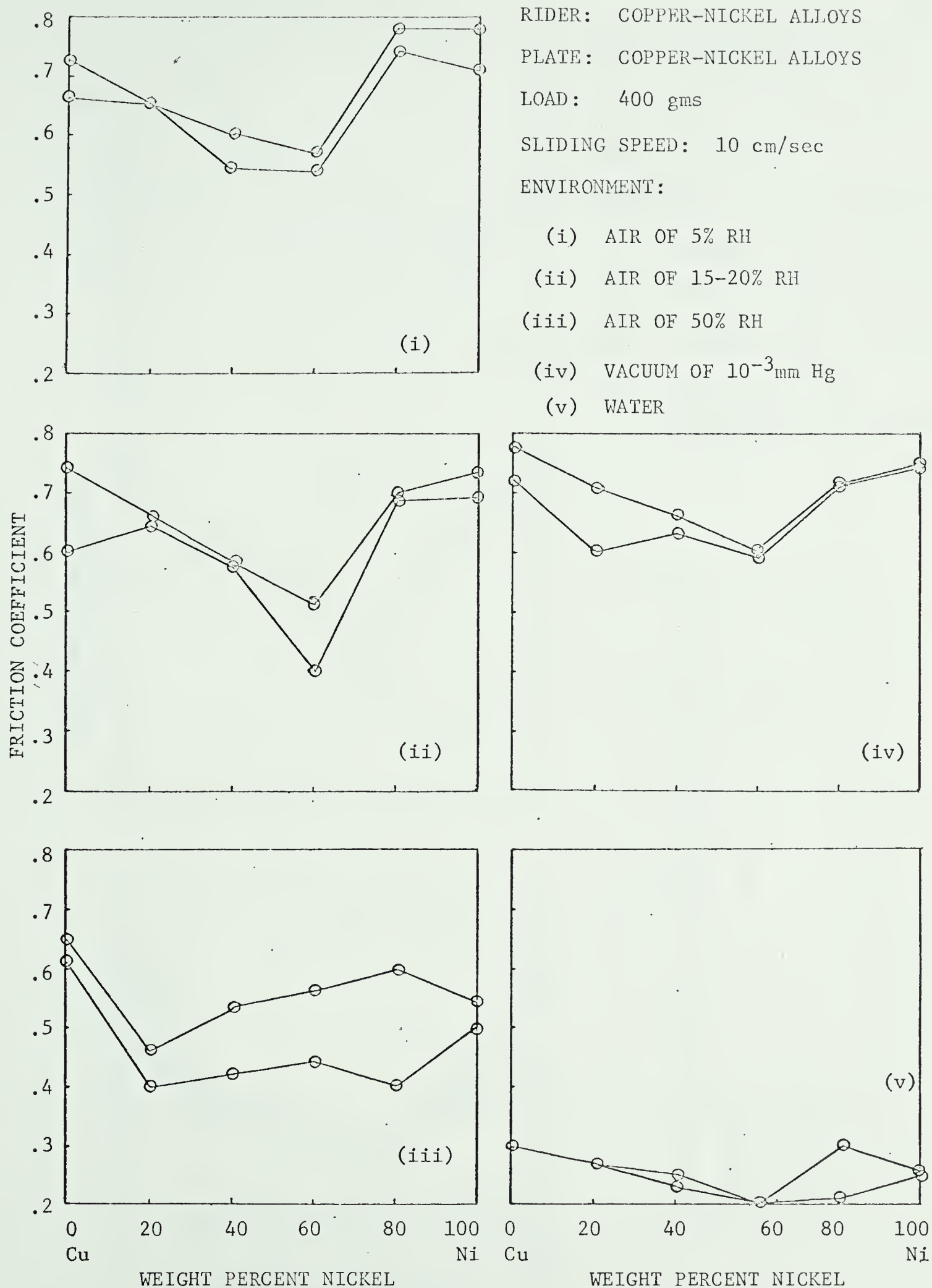


FIG. 4 - FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN DIFFERENT ENVIRONMENTS



RIDER: COPPER-NICKEL ALLOYS

PLATE: COPPER-NICKEL ALLOYS

LOAD: 400 gms

ENVIRONMENT: AIR OF 15-20% RH

(i) SLIDING SPEED - 90 cm/sec

(ii) SLIDING SPEED - 10 cm/sec

(iii) SLIDING SPEED - 2 cm/sec

(iv) AVERAGE FRICTION COEFFICIENT AS A FUNCTION OF SPEED

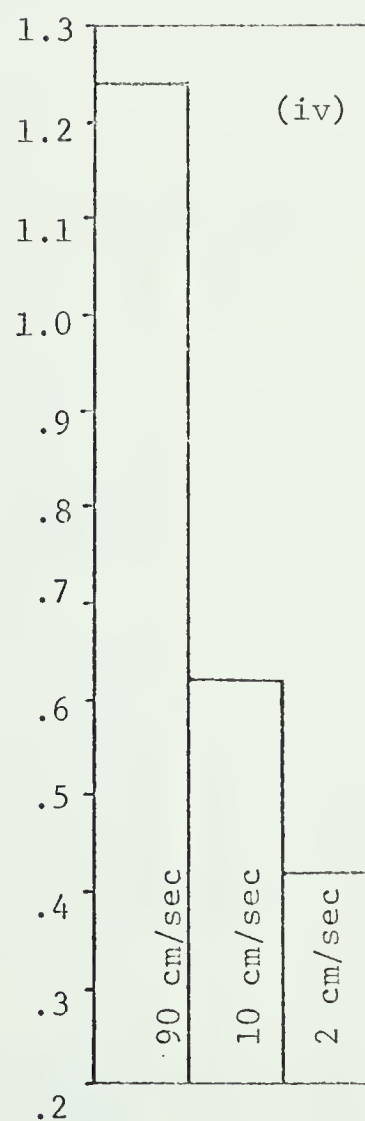


FIG. 5 - FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES AT DIFFERENT SPEEDS IN AIR OF 15-20% RH

RIDER: 52100 STEEL

PLATE: COPPER-NICKEL ALLOYS

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT: AIR OF 15-20% RH

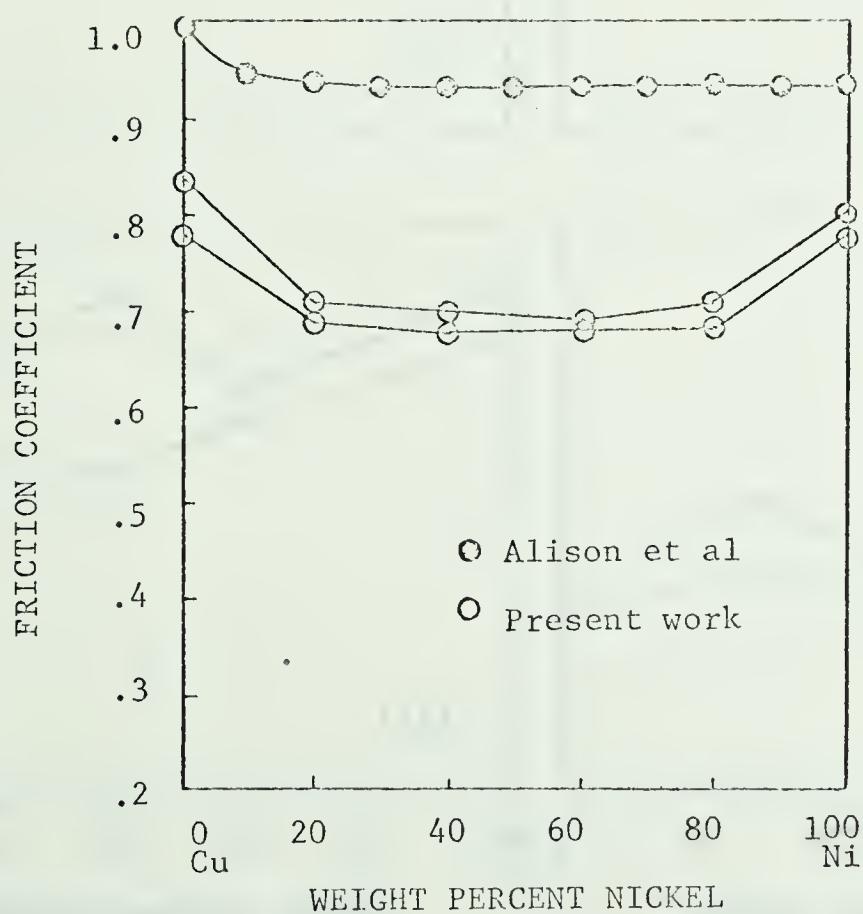


FIG. 6 - FRICTION COEFFICIENTS OF A 52100 STEEL ON COPPER-NICKEL ALLOYS
IN AIR OF 15-20% RH

RIDER: COPPER-NICKEL ALLOYS

PLATE: 1015 STEEL, R_B 65

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT:

(i) AIR OF 5% RH

(ii) AIR OF 15-20% RH

(iii) AIR OF 50% RH

(iv) VACUUM OF 10^{-3} mm Hg

(v) WATER

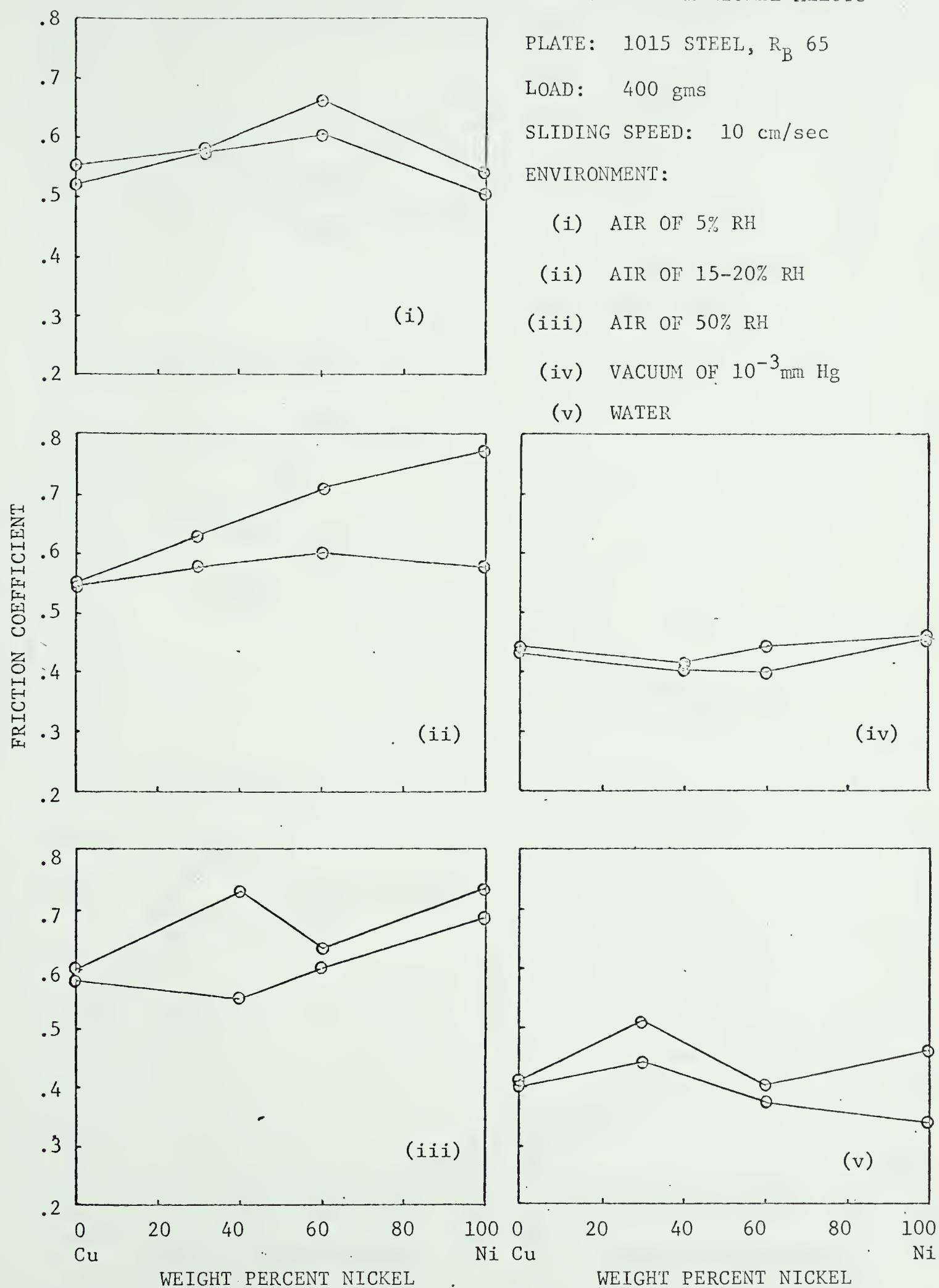


FIG. 7 - FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 1015 STEEL IN DIFFERENT ENVIRONMENTS

RIDER: COPPER-NICKEL ALLOYS

PLATE: 304 STEEL, R_B 82

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT:

(i) AIR OF 5% RH

(ii) AIR OF 15-20% RH

(iii) AIR OF 50% RH

(iv) VACUUM OF 10^{-3} mm Hg

(v) WATER

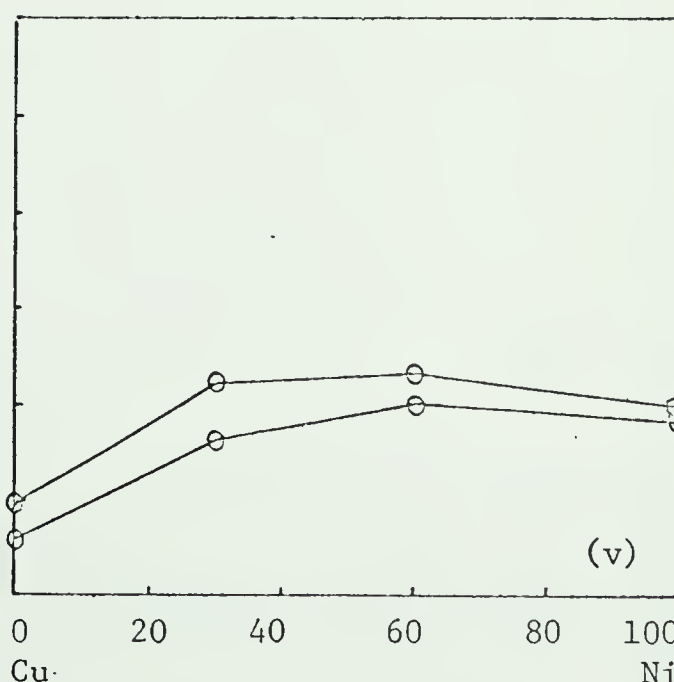
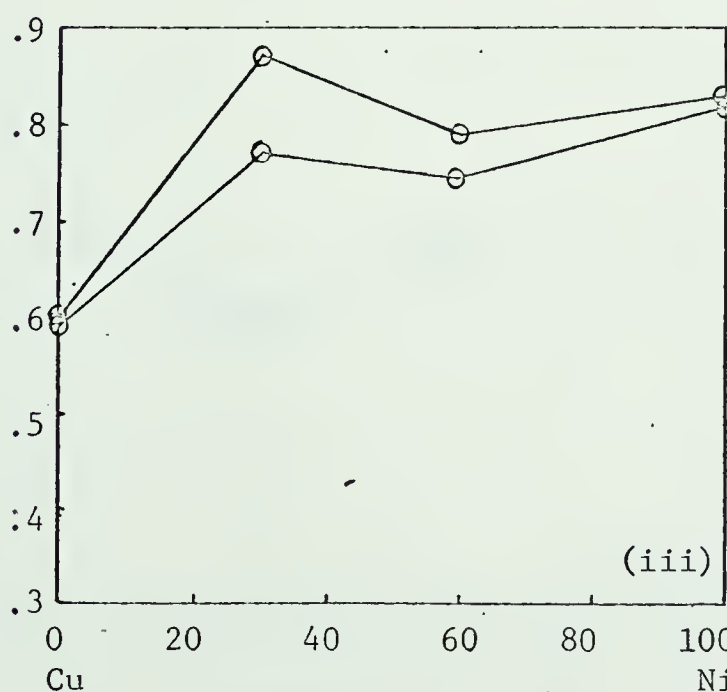
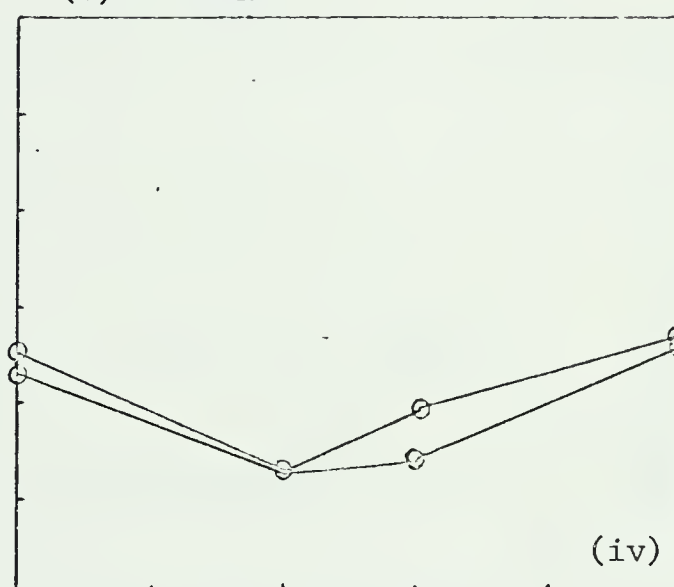
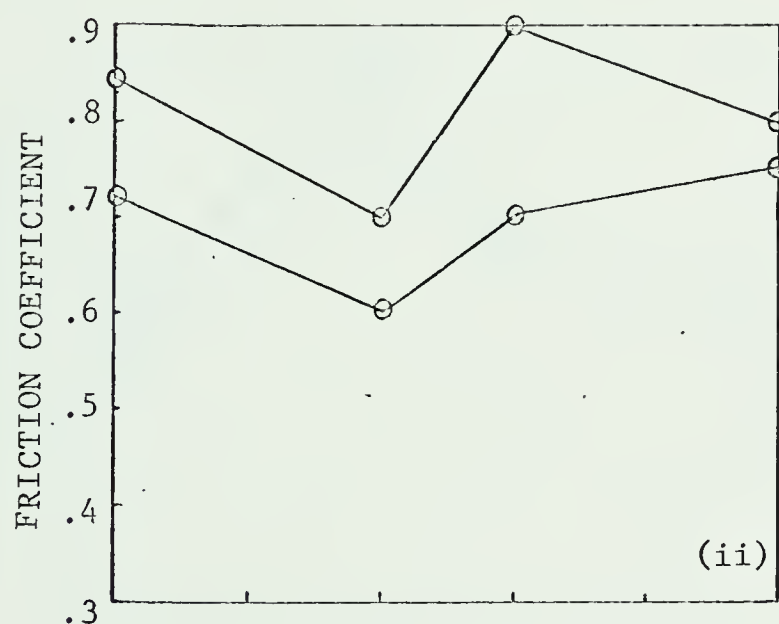
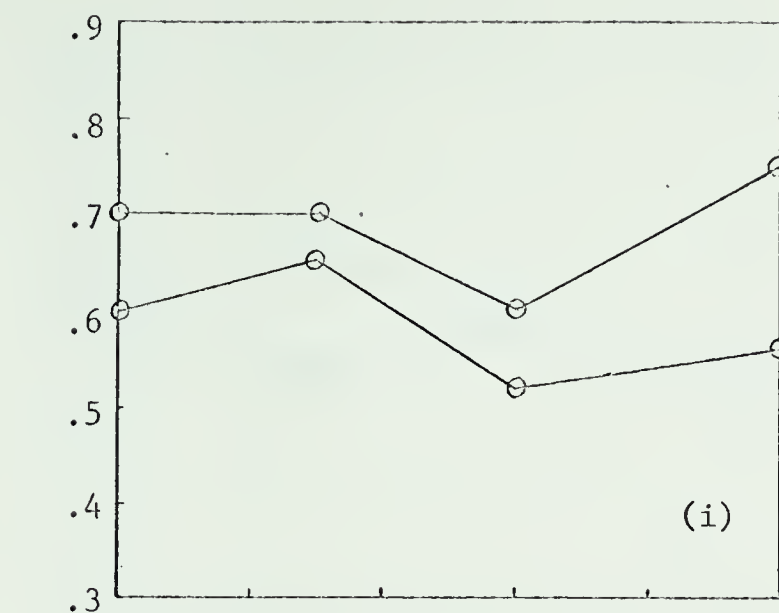


FIG. 8 - FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 304 STEEL IN DIFFERENT ENVIRONMENTS

RIDER: COPPER-NICKEL ALLOYS

PLATE: 01 STEEL, P_B 65

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT:

(i) AIR OF 5% RH

(ii) AIR OF 15-20% RH

(iii) AIR OF 50% RH

(iv) VACUUM OF 10^{-3} mm Hg

(v) WATER

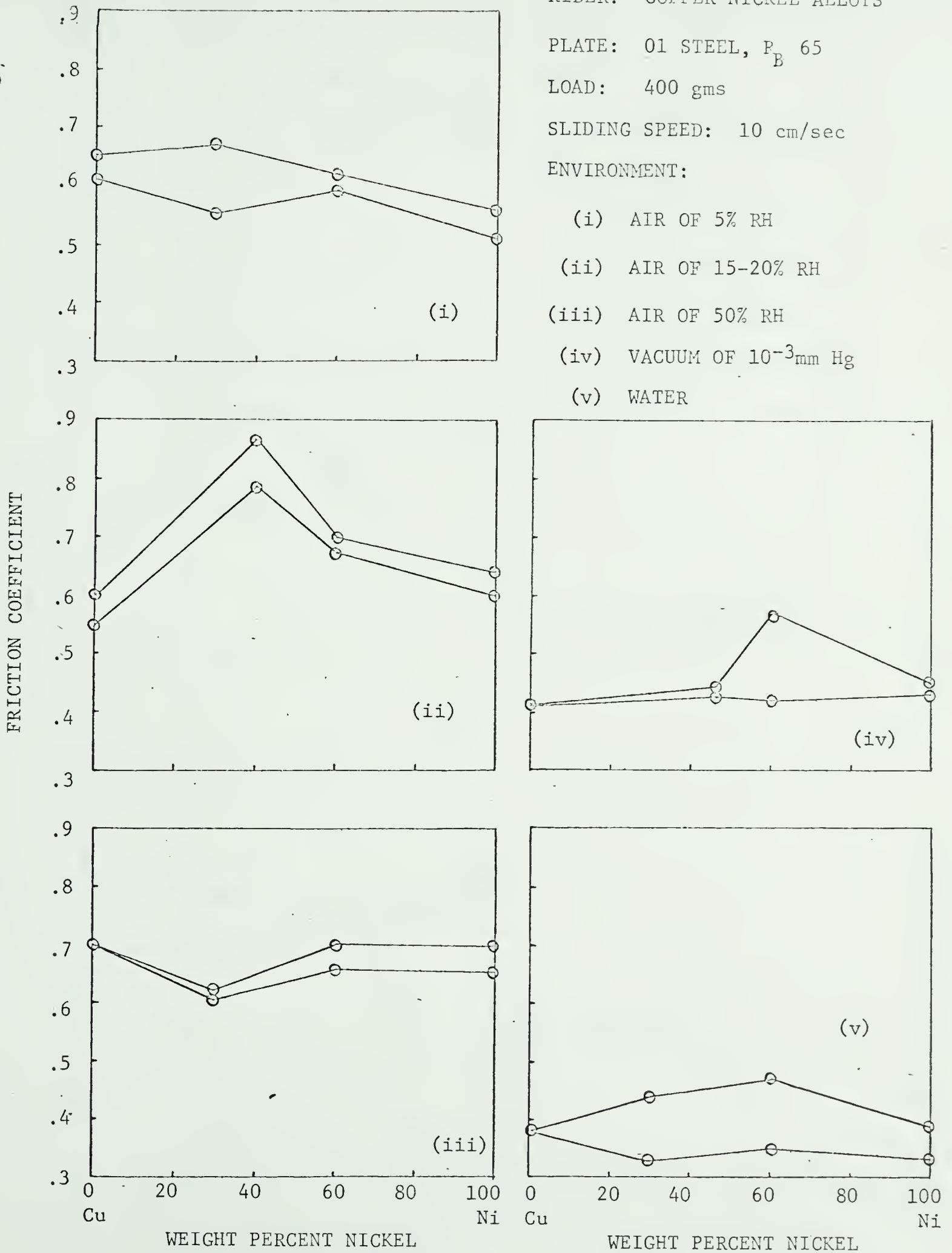


FIG. 9 - FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 65 IN DIFFERENT ENVIRONMENTS

RIDER: COPPER-NICKEL ALLOYS

PLATE: 01 STEEL, R_C 38

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT:

(i) AIR OF 5% RH

(ii) AIR OF 15-20% RH

(iii) AIR OF 50% RH

(iv) VACUUM OF 10^{-3} mm Hg

(v) WATER

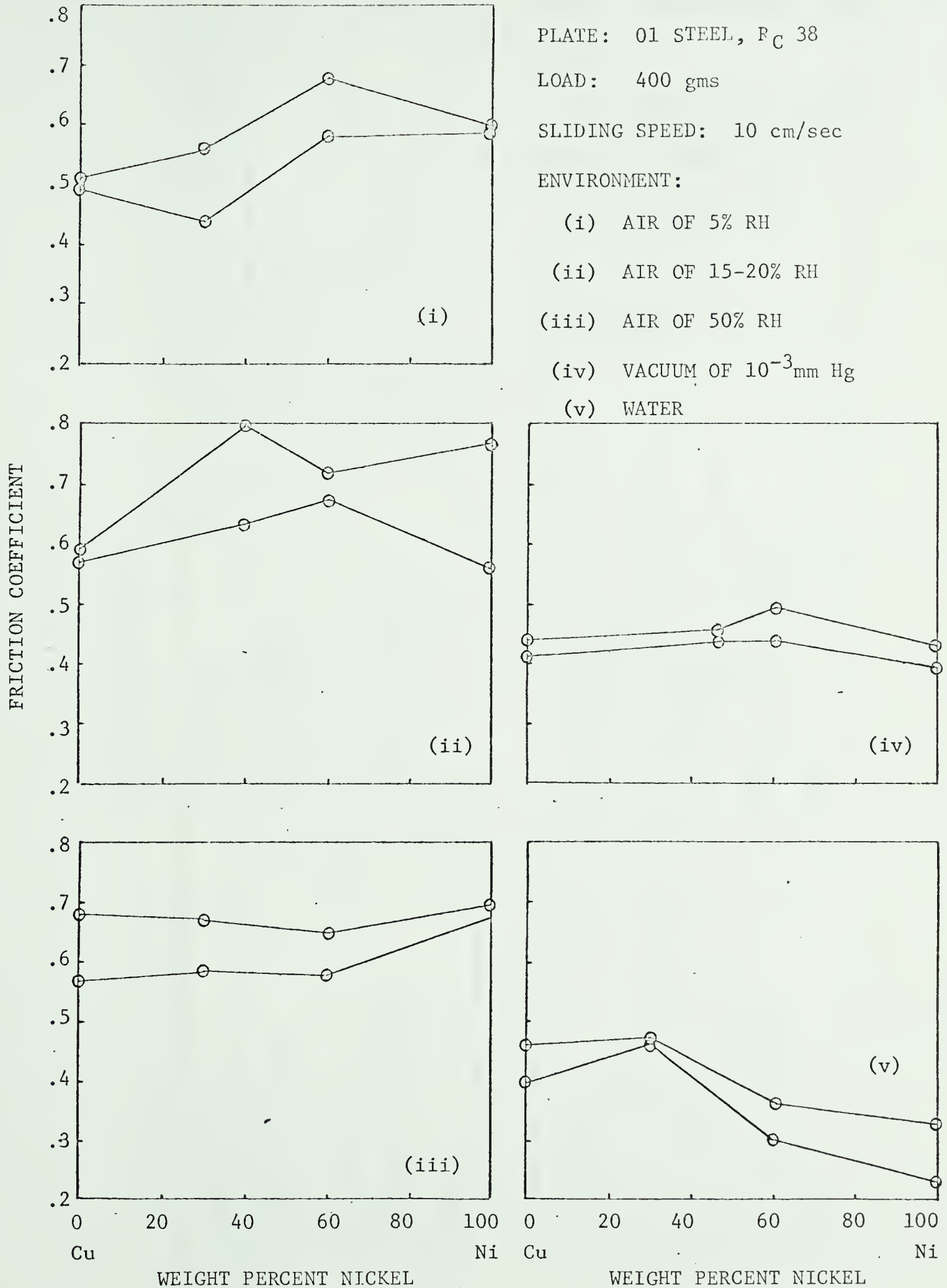


FIG. 10 - FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 38 IN DIFFERENT ENVIRONMENTS

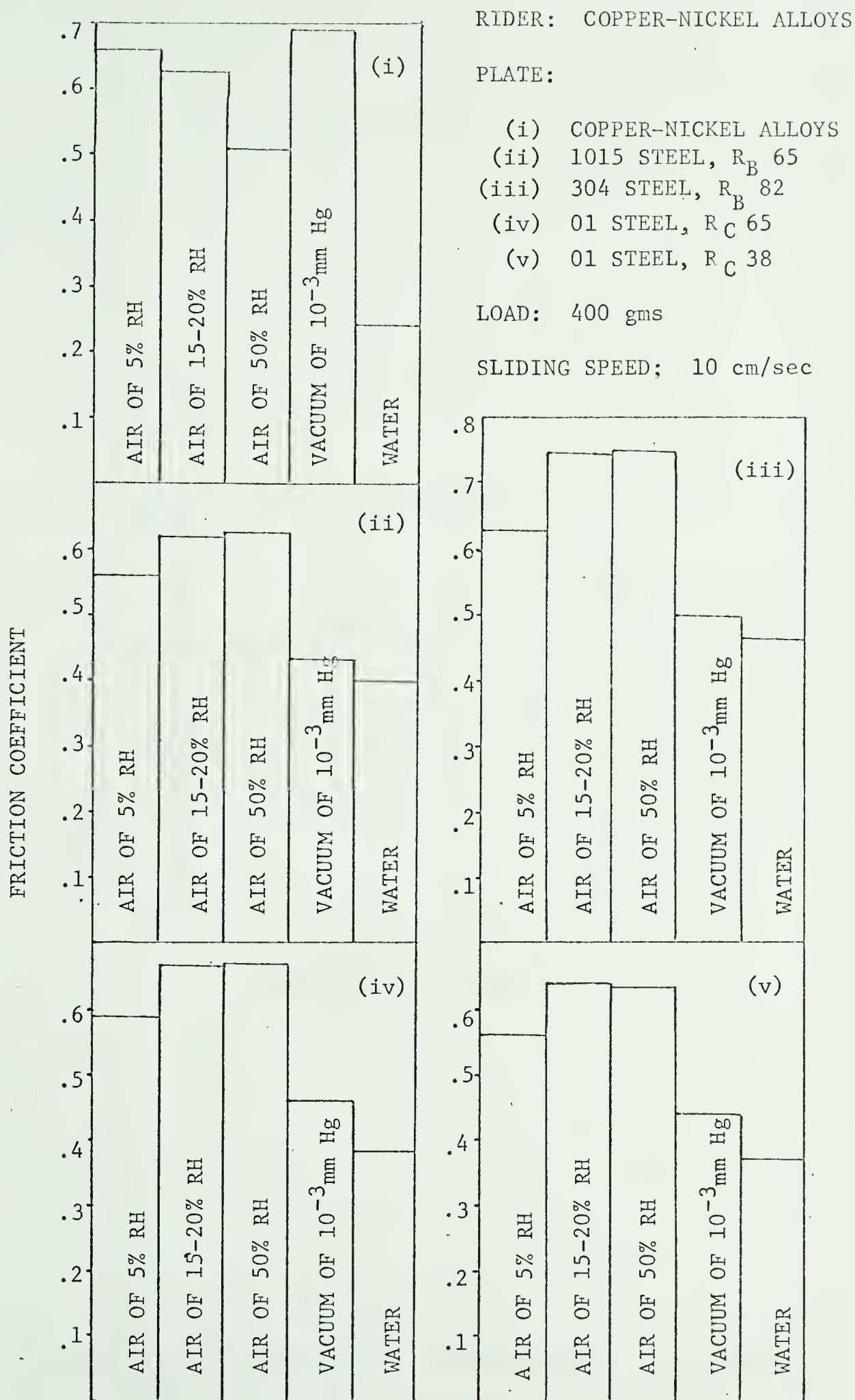


FIG. 11 - AVERAGE FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON DIFFERENT PLATES IN DIFFERENT ENVIRONMENTS

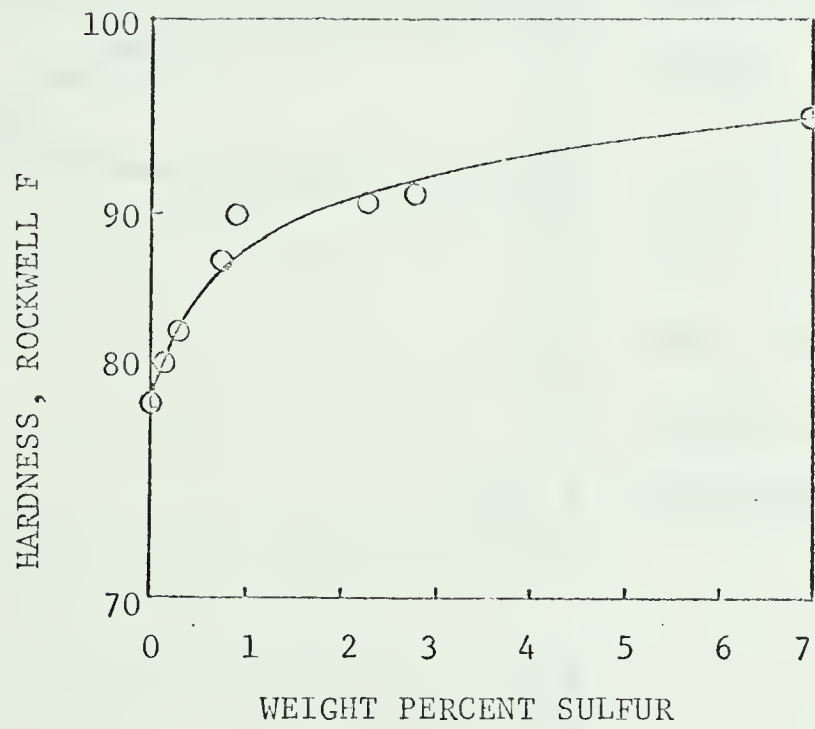
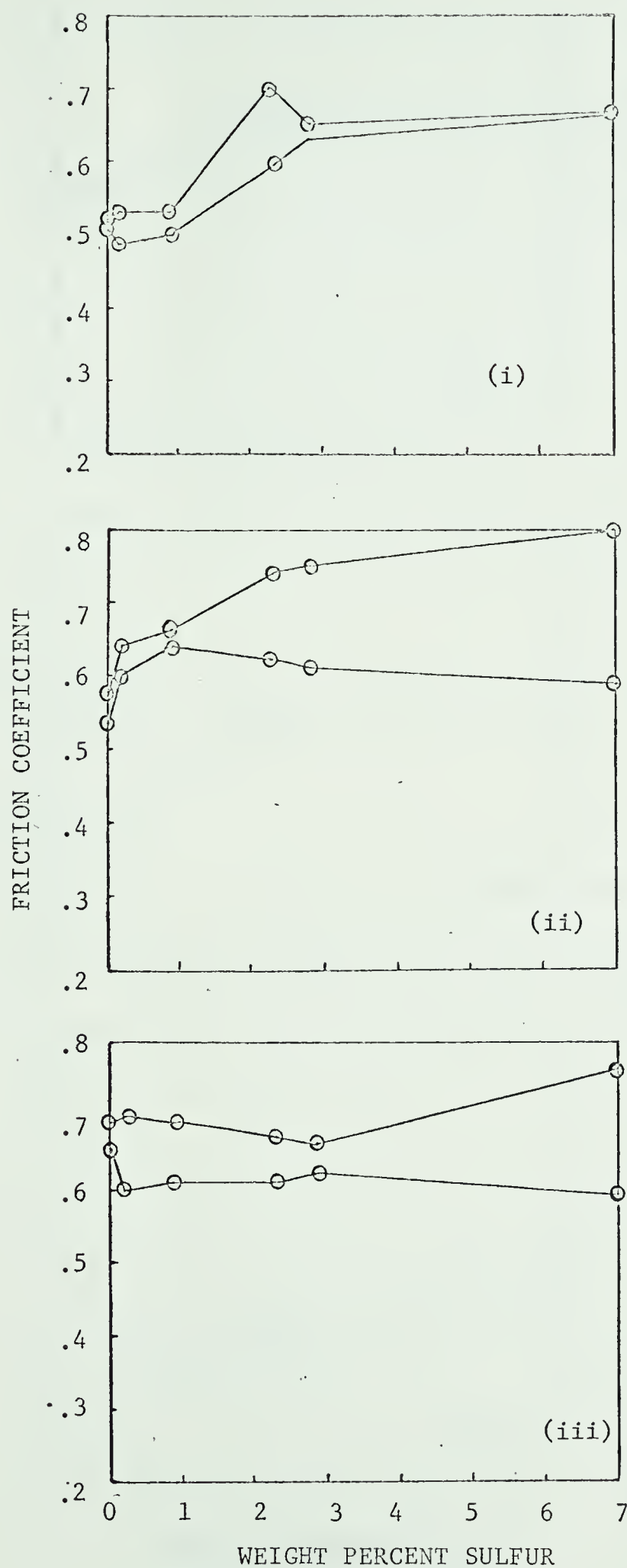


FIG. 12 - VARIATION OF HARDNESS WITH COMPOSITION OF IRON-SULFUR ALLOYS



RIDER: IRON-SULFUR ALLOYS

PLATE:

(i) 1015 STEEL, $R_B = 65$

(ii) 4340 STEEL, $R_C = 48$

(iii) 304 STEEL, $R_B = 82$

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT: AIR OF 15-20% RH

FIG. 13 - FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON DIFFERENT STEEL PLATES IN AIR OF 15-20% RH

RIDER: IRON-SULFUR ALLOYS

PLATE: 1015 STEEL, R_B 65

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT:

(i) AIR OF 15-20% RH

(ii) AIR OF 50% RH

(iii) WATER

(iv) VACUUM OF 10^{-3} mm Hg

FRICTION COEFFICIENT

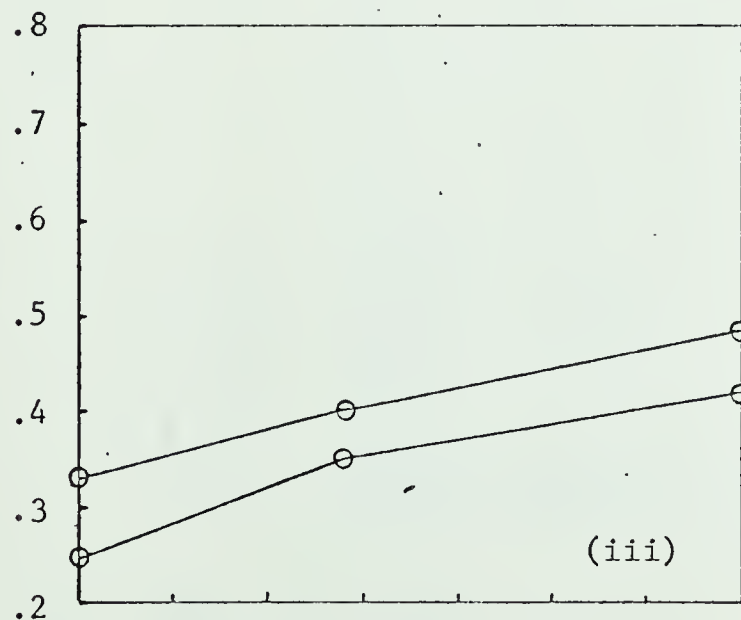
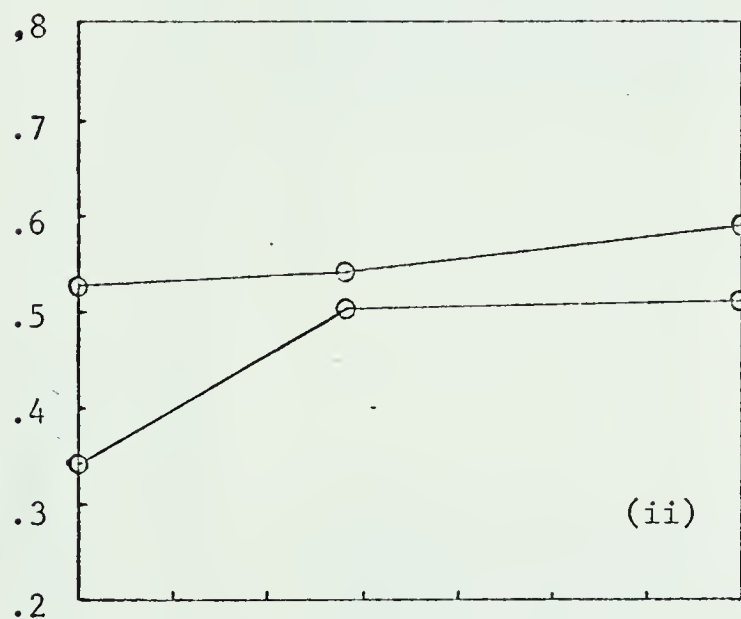
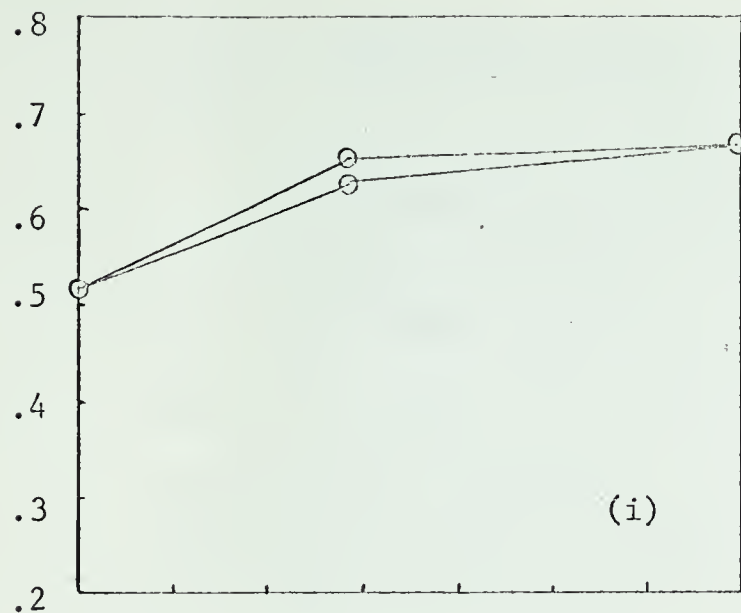


FIG. 14 - FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 1015 STEEL IN DIFFERENT ENVIRONMENTS

RIDER: IRON-SULFUR ALLOYS

PLATE:

- (i) 1015 STEEL, R_B 65
- (ii) 4340 STEEL, R_C 48
- (iii) 304 STEEL, R_B 82

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT: AIR OF 15-20% RH

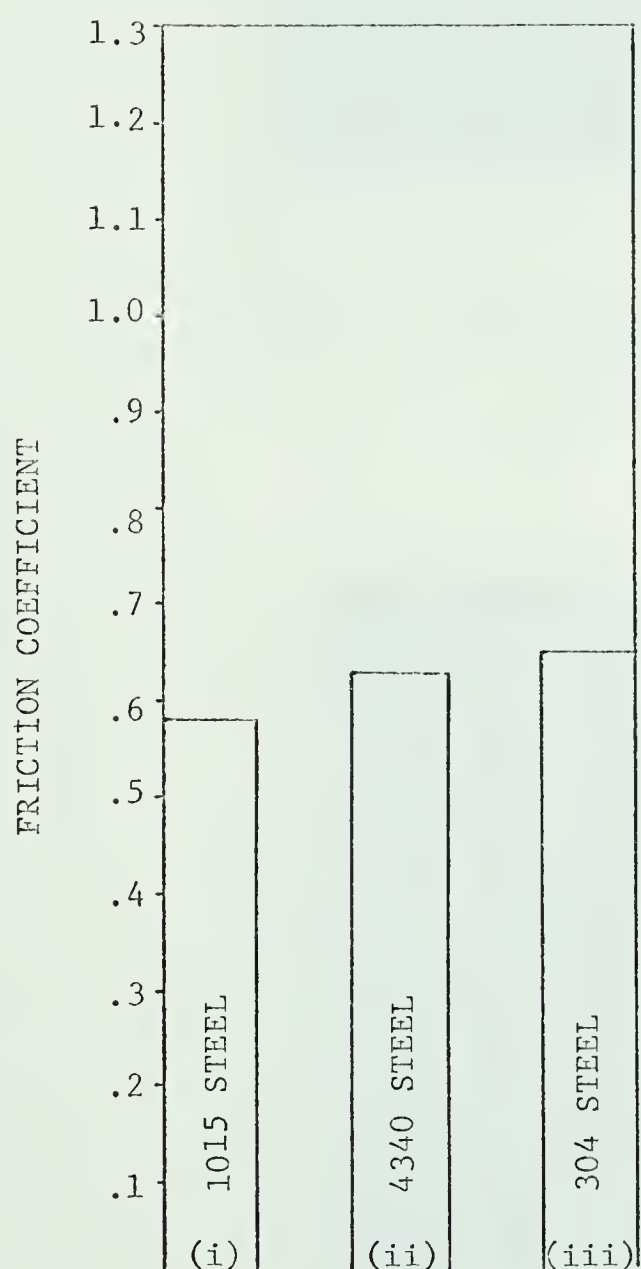


FIG. 15 - AVERAGE FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON DIFFERENT STEEL PLATES IN AIR OF 15-20% RH

RIDER: IRON-SULFUR ALLOYS

PLATE: 1015 STEEL, R_B 65

LOAD: 400 gms

SLIDING SPEED: 10 cm/sec

ENVIRONMENT:

- (i) AIR OF 15-20% RH
- (ii) AIR OF 50% RH
- (iii) VACUUM OF 10^{-3} mm Hg
- (iv) WATER

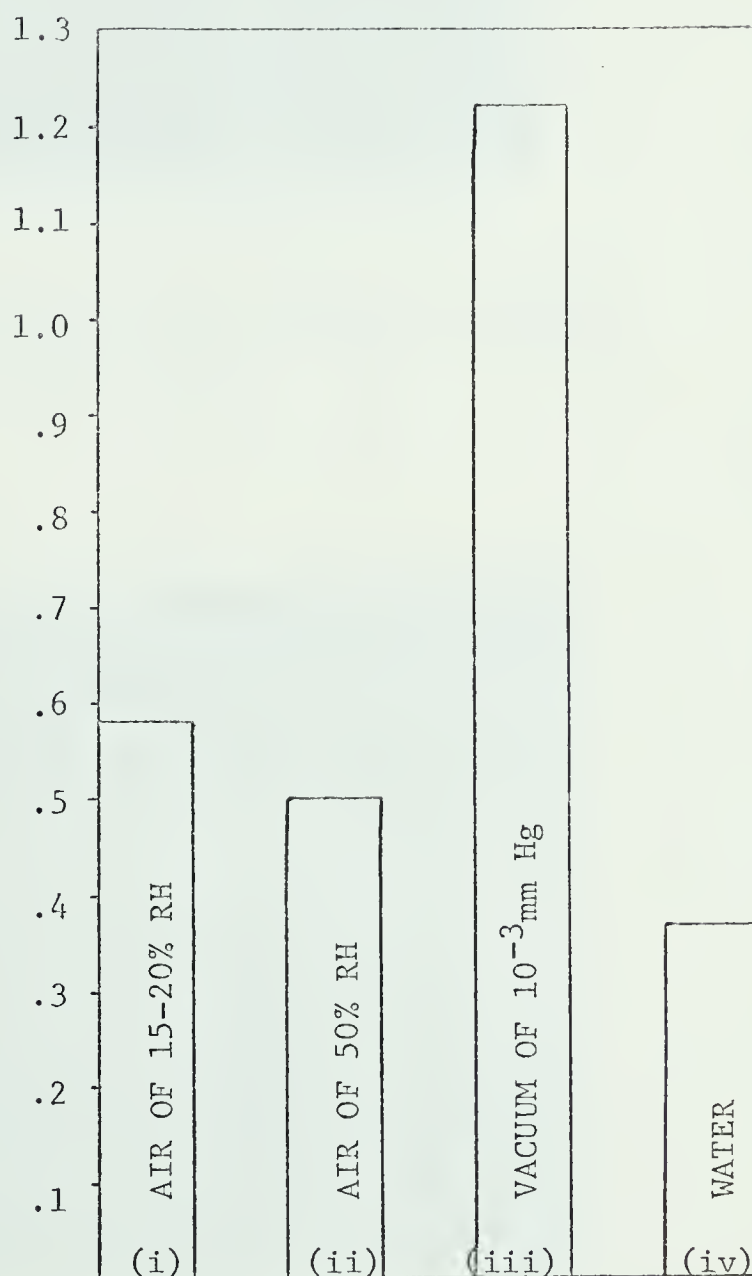


FIG. 16 - AVERAGE FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 1015 STEEL IN DIFFERENT ENVIRONMENTS



FIG. 17 - WEAR TRACK PRODUCED ON 1015 STEEL BY A COPPER RIDER IN VACUUM, X350



FIG. 18 - PHOTOMICROGRAPH OF A COPPER RIDER SURFACE AFTER SLIDING ON 01 STEEL OF R_C 65 IN VACUUM, X350

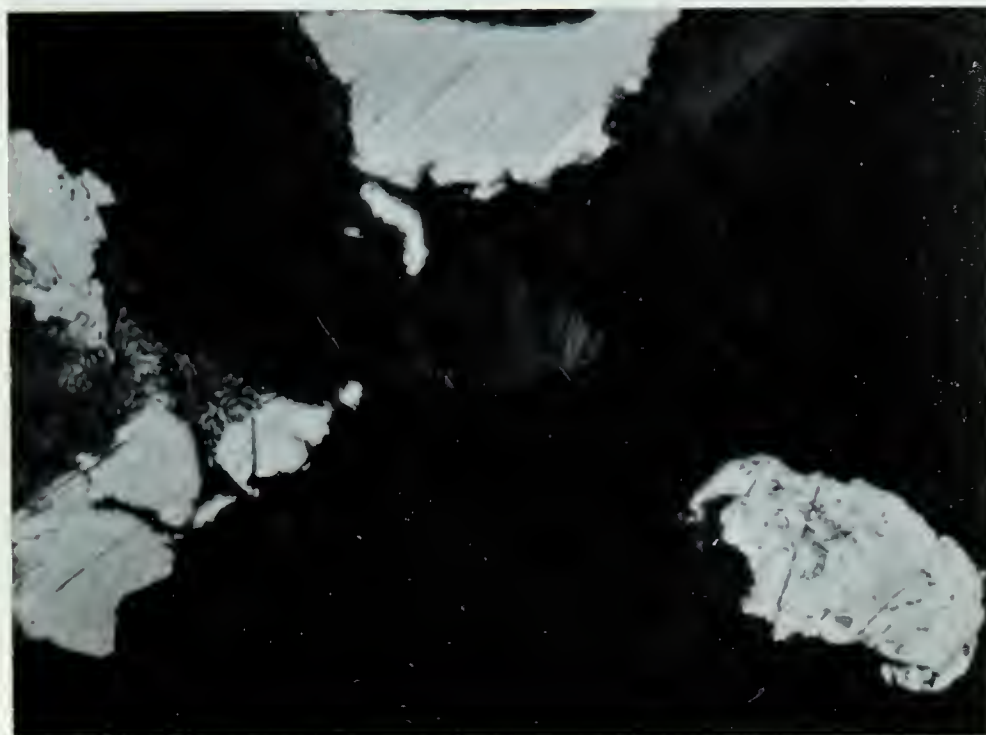


FIG. 19 - PHOTOMICROGRAPH OF WEAR PARTICLES FROM A COPPER-
1015 STEEL FRICTION COUPLE SLIDING IN
VACUUM, X550



FIG. 20 - PHOTOMICROGRAPH OF A WEAR-TRACK ON 1015 STEEL
IN AIR OF 15-20% RH, X350

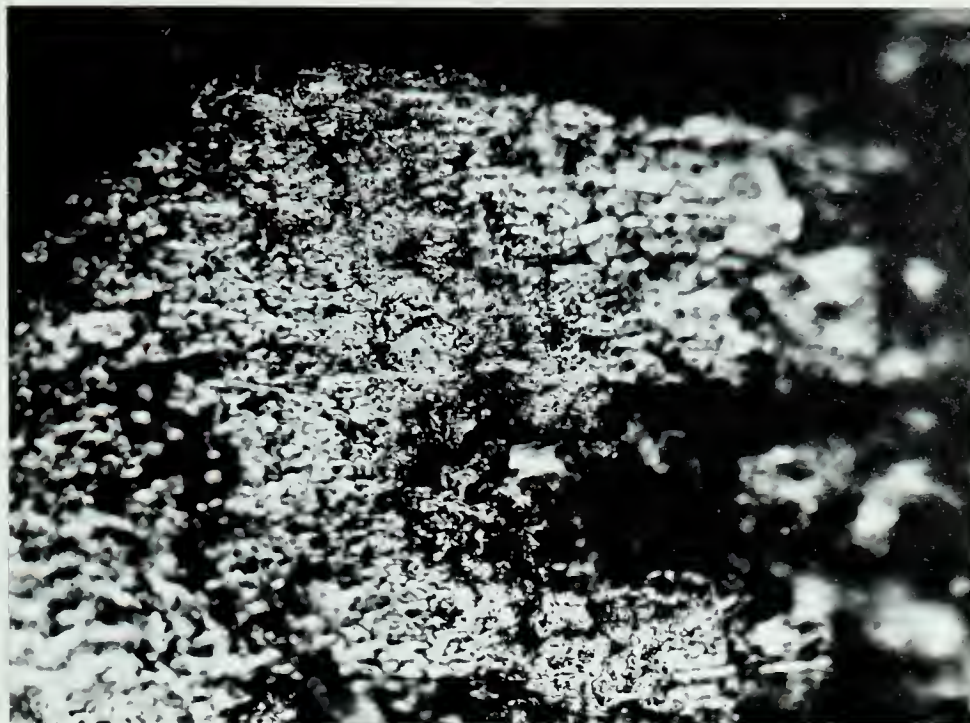


FIG. 21 - PHOTOMICROGRAPH OF A COPPER RIDER SURFACE AFTER
SLIDING ON 1015 STEEL IN AIR OF 15-20% RH, X350

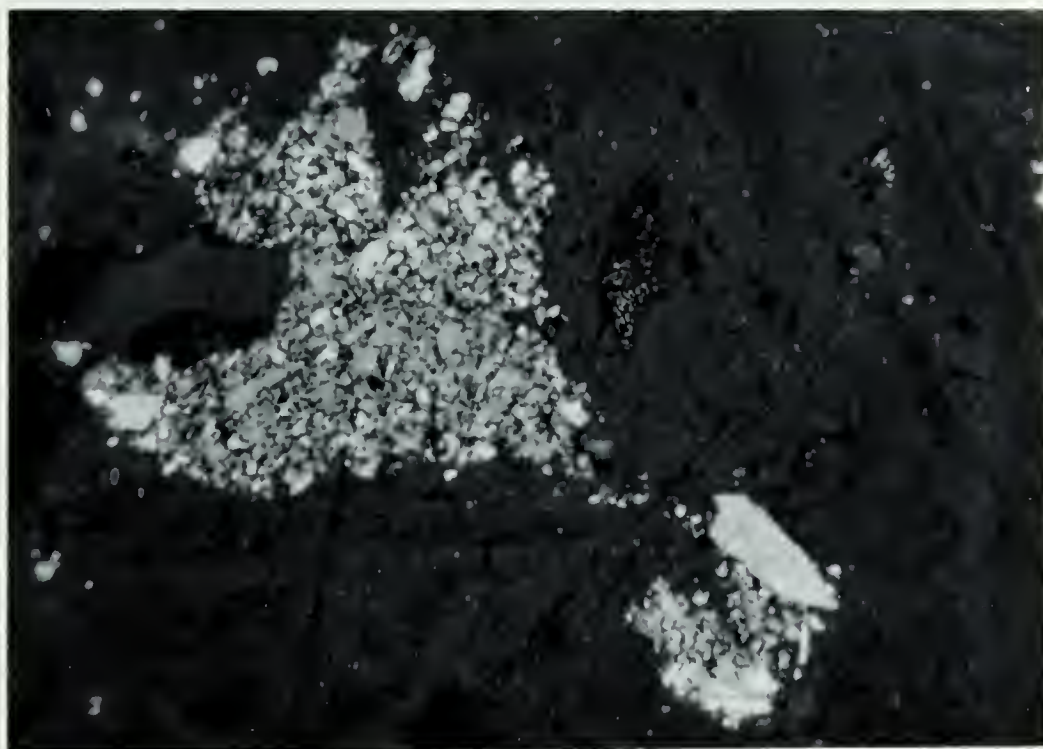


FIG. 22 - PHOTOMICROGRAPH OF WEAR PARTICLES FROM A COPPER-
1015 STEEL FRICTION COUPLE SLIDING IN AIR OF 15-20% RH, X550

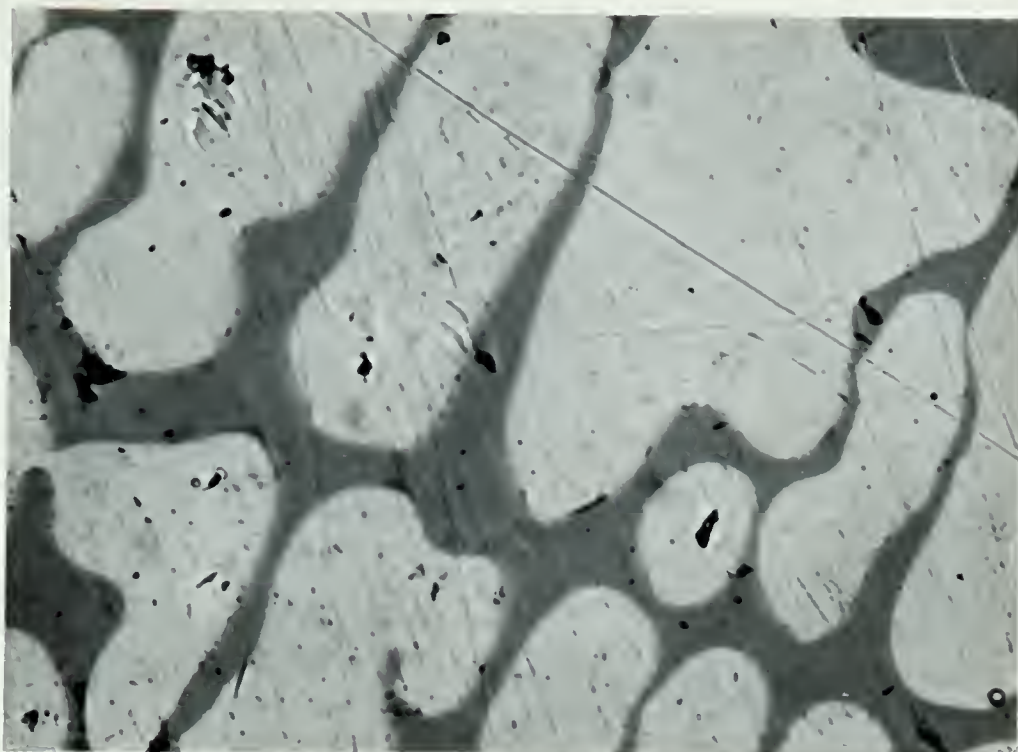


FIG. 23 - MICROSTRUCTURE OF A TYPICAL IRON-SULFUR ALLOY
BEFORE FRICTION TEST, X675

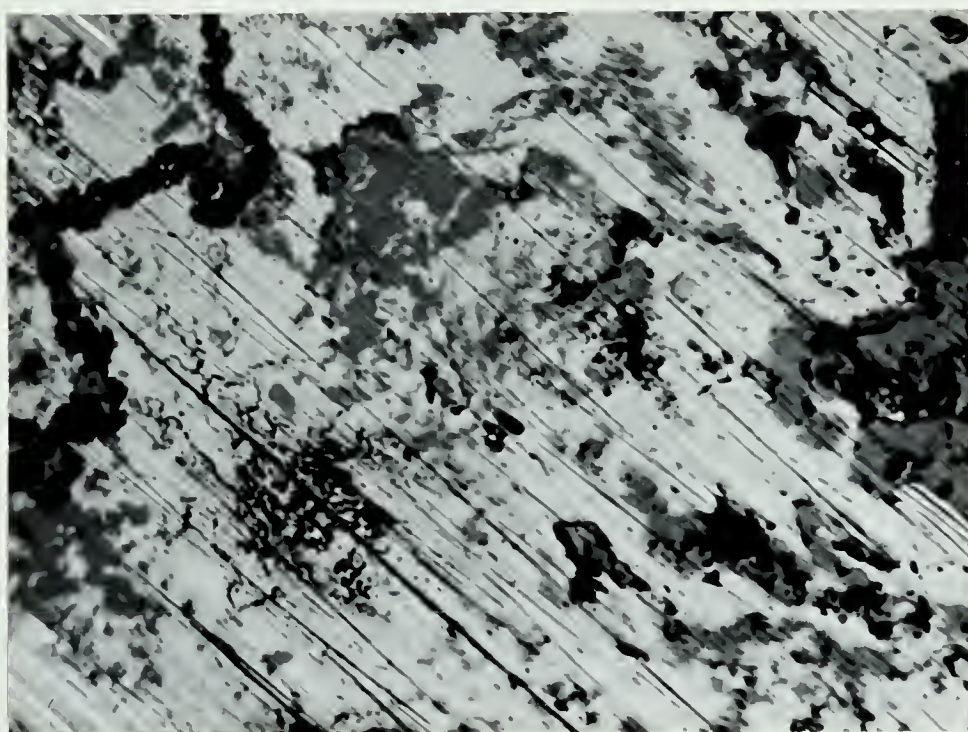


FIG. 24 - MICROSTRUCTURE OF A TYPICAL IRON-SULFUR ALLOY
AFTER FRICTION TEST, X675

APPENDIX-1

FORM, PURITY AND SUPPLIER OF MATERIALS:

A. COPPER SHOT CAT. NO. C - 430 LOT NO. 745630

ANALYSIS

ASSAY	99.93%
INSOLUBLE IN HNO ₃	.004%
ANTIMONY AND TIN (AS TIN)	.0004%
ARSENIC	.0005%
IRON	.001%
LEAD	.0002%
MANGANESE	.001%
PHOSPHORUS	.0006%
SILVER	.0005%

SUPPLIER: FISHER SCIENTIFIC COMPANY, FAIR LAWN, NEW JERSEY, U.S.A.

B. NICKEL POWDER NO. 2575 GRADE S

ANALYSIS

NICKEL	BALANCE
COBALT	.068%
COPPER	.0078%
IRON	.011%
SULFUR	.02%
CARBON	.008%

SUPPLIER: SHERRITT GORDON MINES LIMITED, FORT SASKATCHEWAN,
ALBERTA

C. IRON POWDER NO. 280 LOT NO. 101

ANALYSIS

MANGANESE	.19%
INSOLUBLE	.05%

CARBON	.02%
SULFUR	.007%
H ₂ LOSS	.25%
IRON	BALANCE

SUPPLIER: PEACE RIVER MINING AND SMELTING LIMITED, ALBERTA.

D. FLOWERS OF SULFUR CAT. NO. S-591 LOT NO. 754036

SUPPLIER: FISHER SCIENTIFIC COMPANY, FAIR LAWN, NEW JERSEY,
U.S.A.

TABLE I
ANALYSIS AND HARDNESS OF COPPER-NICKEL ALLOYS

MATERIAL DESIGNATION	WEIGHT PERCENT NICKEL	WEIGHT PERCENT COPPER	BULK HARDNESS ROCKWELL F
N-0	Nil	100.0	51.0
N-2	19.8	80.2	65.0
N-3	31.0	69.0	71.0
N-4	39.1	60.9	77.0
N-6	59.8	40.2	85.0
N-8	79.1	20.9	83.5
N-10	100.0	Nil	81.0

TABLE 2

FRICITION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN AIR OF 5% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICITION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.72	.66	.66
N-2	.65	.65	
N-4	.60	.54	
N-6	.57	.54	
N-8	.74	.78	
N-10	.71	.78	

TABLE 3

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN AIR OF 15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.60	.74	.62
N-2	.64	.64	
N-4	.58	.58	
N-6	.40	.51	
N-8	.69	.70	
N-10	.74	.69	

TABLE 4

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN AIR OF 50% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.65	.61	.51
N-2	.46	.40	
N-4	.42	.53	
N-6	.56	.44	
N-8	.40	.60	
N-10	.50	.54	

TABLE 5

FRICITION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN VACUUM OF
 10^{-3} mm Hg AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICITION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.72	.78	.69
N-2	.60	.71	
N-4	.66	.63	
N-6	.60	.59	
N-8	.71	.71	
N-10	.74	.75	

TABLE 6

FRICITION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN WATER AT
 A SLIDING SPEED OF 10 cm/sec

RIDER	FRICITION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.30	.30	.25
N-2	.27	.27	
N-4	.25	.23	
N-6	.20	.20	
N-8	.30	.21	
N-10	.25	.26	

TABLE 7

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN AIR OF
15-20% RH AT A SLIDING SPEED OF 90 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	1.30	1.24	1.23
N-2	1.42	1.20	
N-4	1.20	1.13	
N-6	1.24	1.14	
N-8	1.10	1.16	
N-10	1.20	1.25	

TABLE 8

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON THEMSELVES IN AIR OF
15-20% RH AT A SLIDING SPEED OF 2 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.50	.69	.42
N-2	.39	.40	
N-4	.37	.36	
N-6	.32	.28	
N-8	.40	.42	
N-10	.45	.60	

TABLE 9

FRICTION COEFFICIENTS OF A 52100 STEEL ON COPPER-NICKEL ALLOYS IN AIR OF
15-20% RH AT A SLIDING SPEED OF 10 cm/sec

PLATE	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.84	.78	.73
N-2	.71	.70	
N-4	.68	.70	
N-6	.69	.68	
N-8	.71	.68	
N-10	.80	.78	

TABLE 10

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 1015 STEEL IN AIR OF 5%
RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.55	.52	.56
N-3	.57	.58	
N-6	.60	.66	
N-10	.50	.54	

TABLE 11

FRICITION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 1015 STEEL IN AIR OF
15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICITION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.54	.55	.62
N-3	.63	.58	
N-6	.71	.60	
N-10	.77	.58	

TABLE 12

FRICITION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 1015 STEEL IN AIR OF 50%
RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICITION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.60	.58	.63
N-4	.73	.55	
N-6	.60	.63	
N-10	.68	.73	

TABLE 13

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 1015 STEEL IN VACUUM OF
 10^{-3} mm Hg AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.43	.44	.43
N-4	.40	.41	
N-6	.40	.44	
N-10	.46	.45	

TABLE 14

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 1015 STEEL IN WATER AT
 A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.40	.41	.42
N-3	.44	.51	
N-6	.37	.40	
N-10	.34	.46	

TABLE 15

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 304 STEEL IN AIR OF 5% RH
AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.70	.60	
N-3	.65	.70	
N-6	.60	.52	.63
N-10	.75	.56	

TABLE 16

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 304 STEEL IN AIR OF 15-
20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.72	.84	
N-4	.70	.60	.75
N-6	.90	.70	
N-10	.75	.80	

TABLE 17

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 304 STEEL IN AIR OF 50% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.59	.60	.75
N-3	.77	.87	
N-6	.74	.79	
N-10	.82	.83	

TABLE 18

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 304 STEEL IN VACUUM OF 10^{-3} mm Hg AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.55	.53	.50
N-4	.43	.43	
N-6	.49	.44	
N-10	.57	.56	

TABLE 19

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 304 STEEL IN WATER AT
A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.36	.39	.47
N-3	.46	.52	
N-6	.53	.50	
N-10	.48	.50	

TABLE 20

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_c 65 IN AIR
OF 5% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.61	.65	.60
N-3	.55	.67	
N-6	.62	.59	
N-10	.56	.51	

TABLE 21

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 65 IN
AIR OF 15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.55	.59	.68
N-4	.87	.79	
N-6	.69	.68	
N-10	.60	.64	

TABLE 22

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 65 IN
AIR OF 50% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.70	.70	.67
N-3	.61	.63	
N-6	.66	.70	
N-10	.70	.65	

TABLE 23

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 65 IN
VACUUM OF 10^{-3} mm Hg AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.41	.41	.46
N-4	.44	.43	
N-6	.57	.42	
N-10	.43	.45	

TABLE 24

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 65 IN
WATER AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.38	.38	.38
N-3	.33	.44	
N-6	.35	.47	
N-10	.33	.39	

TABLE 25

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 38 IN
AIR OF 5% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.51	.49	.56
N-3	.44	.56	
N-6	.68	.58	
N-10	.60	.59	

TABLE 26

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 38 IN
AIR OF 15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.59	.57	.64
N-4	.80	.64	
N-6	.72	.67	
N-10	.56	.77	

TABLE 27

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 38 IN
AIR OF 50% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.57	.68	.64
N-3	.67	.58	
N-6	.59	.65	
N-10	.70	.67	

TABLE 28

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 38 IN
VACUUM OF 10^{-3} mm Hg AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.41	.44	.44
N-4	.44	.45	
N-6	.44	.47	
N-10	.43	.39	

TABLE 29

FRICTION COEFFICIENTS OF COPPER-NICKEL ALLOYS ON 01 STEEL OF R_C 38 IN
WATER AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
N-0	.40	.46	.37
N-3	.46	.47	
N-6	.36	.30	
N-10	.23	.33	

TABLE 30

ANALYSIS AND HARDNESS OF IRON-SULFUR ALLOYS

MATERIAL DESIGNATION	WEIGHT PERCENT SULFUR	WEIGHT PERCENT IRON	BULK HARDNESS ROCKWELL F
F-1	Nil	100.00	80.0
F-2	0.23	99.77	83.0
F-3	0.37	99.63	84.0
F-4	0.79	99.21	87.5
F-5	0.93	99.07	90.0
F-6	2.30	97.70	90.5
F-7	2.81	97.19	91.0
F-8	6.98	93.02	95.0

TABLE 31

FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 1015 STEEL IN AIR OF 15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
F-1	.52	.52	.58
F-2	.53	.49	
F-5	.50	.53	
F-6	.70	.59	
F-7	.63	.65	
F-8	.67	.67	

TABLE 32

FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 4340 STEEL IN AIR OF 15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
F-1	.51	.56	.64
F-2	.60	.64	
F-5	.66	.64	
F-6	.74	.62	
F-7	.61	.75	
F-8	.82	.59	

TABLE 33

FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 304 STEEL IN AIR OF 15-20% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
F-1	.67	.69	.66
F-2	.60	.70	
F-5	.61	.69	
F-6	.61	.67	
F-7	.62	.66	
F-8	.59	.76	

TABLE 34

FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 1015 STEEL IN AIR OF 50% RH AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
F-1	.52	.34	.50
F-7	.50	.54	
F-8	.59	.51	

TABLE 35

FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 1015 STEEL IN VACUUM OF 10^{-3}
mm Hg AT A SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
F-1	1.30	.90	1.22
F-7	1.30	1.22	
F-8	1.50	1.32	

TABLE 36

FRICTION COEFFICIENTS OF IRON-SULFUR ALLOYS ON 1015 STEEL IN WATER AT A
SLIDING SPEED OF 10 cm/sec

RIDER	FRICTION COEFFICIENT		
	TEST 1	TEST 2	AVERAGE
F-1	.33	.25	.37
F-7	.35	.40	
F-8	.48	.42	

TABLE 37

X RAY POWDER PATTERN OF THE DEBRIS FROM THE COPPER-1015 STEEL COUPLE IN
AIR OF 15-20% RH, OF COPPER AND IRON FILINGS

d(DEBRIS) ° Å	d (IRON FILINGS) ° Å	d (COPPER FILINGS) ° Å	d (Fe_3O_4) ASTM FILE ° Å	d ($6\text{CuO} \cdot \text{Cu}_2\text{O}$) ASTM FILE ° Å
7.44	7.44			
4.04				4.04
2.91			2.97	2.90
2.48			2.53	2.50 2.47
2.03	2.03	2.09		
1.97	1.97			
1.77		1.77		
1.58			1.61	1.58
1.46			1.48	1.45 1.43
1.41	1.41			
1.26		1.26		
1.16	1.16			
1.08		1.08		
1.03		1.03		
1.01	1.01			

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